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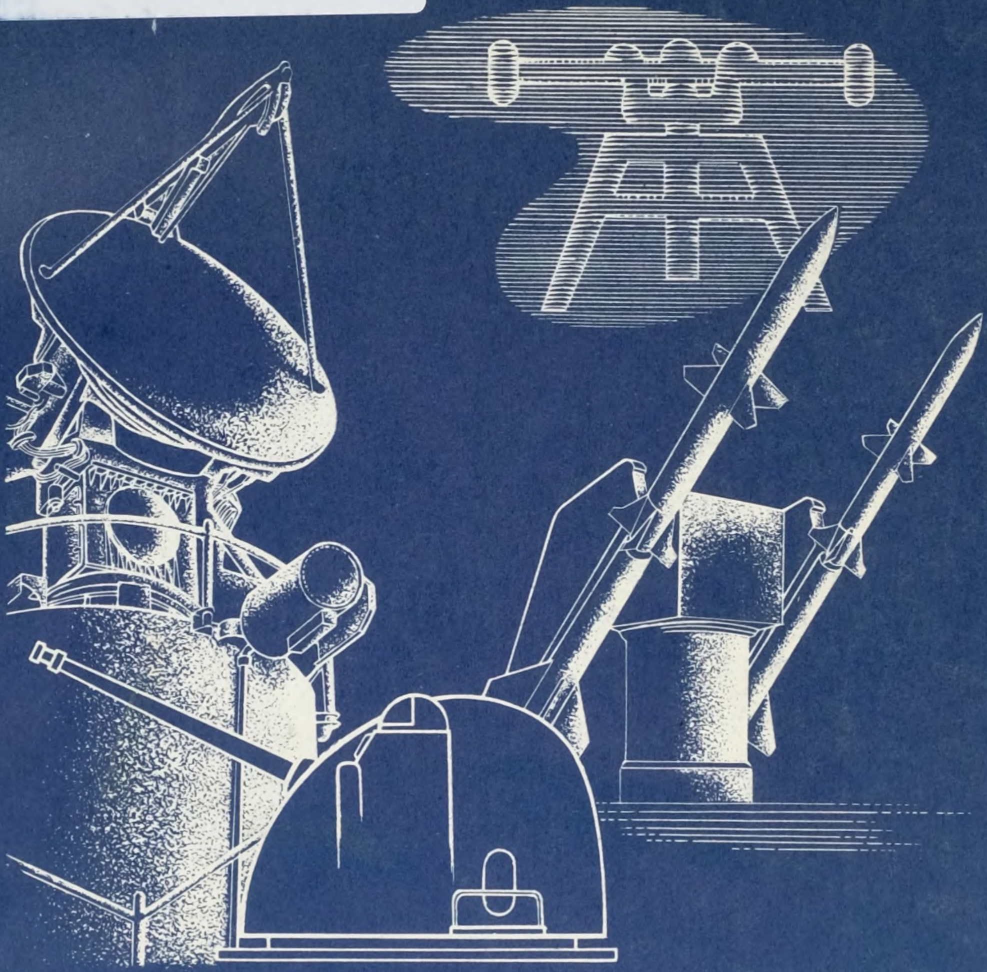

FIRE CONTROL TECHNICIAN 3

BUREAU OF NAVAL PERSONNEL

NAVY TRAINING COURSE NAVPERS 10173-B

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PREFACE

This Navy Training Course was written to serve as an aid for enlisted men of the U. S. Navy and the U. S. Naval Reserve who are preparing for advancement to the rating of Fire Control Technician G (gun fire control) 3 and Fire Control Technician M (missile fire control) 3. It is one of a series of Navy Training Courses designed to give enlisted men background information of the duties of their rate.

The predominant factor in the selection of content for this publication has been the Manual of Qualifications for Advancement in Rating, NavPers 18068-B, as it relates to FTG3 and FTM3. Because the qualifications for the two service ratings are almost the same at this level, it was found advisable to keep the study material in one volume.

This book was prepared for the Bureau of Naval Personnel by the Training Publications Division, Naval Personnel Program Support Activity, Washington, D. C. 20390. Special credit is given to the Bureau of Naval Weapons and to the Fire Control Technician Schools, Great Lakes, Illinois, for assisting in the technical review of the text.

1966 Edition

THE UNITED STATES NAVY

GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

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Basic Machines, 10624-A
Blueprint Reading and Sketching, NavPers 10077-B
Military Requirements for PO 3/2, NavPers 10056-B
Mathematics, Volume I, NavPers 10069-B
Mathematics, Volume II, NavPers 10071-A
Mathematics, Volume III, NavPers 10073
Fire Control Fundamentals, NavPers 91900
Fire Control Radar Fundamentals, NavPers 91901

OTHER PUBLICATIONS

Ordnance Safety Precautions; Their Origin and Necessity, NavWeps OP 1014
Weapons System Fundamentals, Volumes I, II, and III, NavWeps OP 3000
Lubrication of Ordnance Equipment, OD 3000

USAFI COURSES

United States Armed Forces Institute (USAFI) courses for additional reading and study are available through your Information and Education Officer.* A partial list of those courses which should be helpful to the Fire Control Technician follows:

C 781	Fundamentals of Electricity
C 151	General Mathematics I
C 152	General Mathematics II

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*Members of the United States Armed Forces Reserve components, when on active duty, are eligible to enroll for USAFI courses, services and materials if the orders calling them to active duty specify a period of 120 days or more, or if they have been on active duty for a period of 120 days or more, regardless of the time specified in the active duty orders.

CHAPTER 1

INTRODUCTION TO FIRE CONTROL

This training course is designed to help you meet the professional (technical) qualifications for advancement to Fire Control Technician 3. The Fire Control Technician qualifications used as a guide in the preparation of this training course were taken from the current edition of the Manual of Qualifications for Advancement in Rating, NavPers 18068-B. The subject matter in this training course has been organized to give you a systematic understanding of your job.

Chapter 2 of this course discusses the elements of the gun fire control problem. Chapter 3 introduces the guided missile and the basic methods of controlling its flight. Chapter 4 contains a statement of the guided missile problem and some of the modifications to the solution of the problem. Chapter 5 presents an overview of a representative weapons system.

Chapter 6 treats the subjects of tools and "hardware" common to fire control equipment. Synchros and how they are used in fire control are described in chapter 7. Chapter 8 contains basic information on servomechanisms. Chapter 9 considers the gyroscopes in fire control equipment; their use in lead-computing sights is covered in chapter 10.

Chapter 11 discusses the basic principles of analog computers and computing mechanisms. The principles of operation of fire control radars are covered in chapters 12, 13, and 14. The submarine torpedo fire control problem is introduced in chapter 15. The forms and reports you are required to fill out, and the Navy maintenance system, are described in chapter 16. Chapter 17 covers general maintenance, electrical test equipment, and troubleshooting techniques.

The remainder of this chapter gives information on the enlisted rating structure, the Fire Control Technician rating, requirements and procedures for advancement in rating, and references that will help you in working for advancement and in performing your duties as a technician. This chapter includes information on how to use Navy Training Courses. Therefore, it is strongly recommended that you study this chapter carefully before beginning intensive study of the remainder of this training course.

THE ENLISTED RATING STRUCTURE

The two main types of ratings in the present enlisted rating structure, are general ratings and service ratings.

GENERAL RATINGS identify broad occupational fields of related duties and functions. Some general ratings include service ratings; others do not. Both Regular Navy and Naval Reserve personnel may hold general ratings.

SERVICE RATINGS identify subdivisions or specialties within a general rating. Although service ratings can exist at any petty officer level, they are most common at the PO3 and PO2 levels. Both Regular Navy and Naval Reserve personnel may hold service ratings.

THE FIRE CONTROL TECHNICIAN RATING

As Fire Control Technician, you must learn the fire control problem to better enable you to visualize the functions of the equipment in a fire control system. But knowing the theory behind the problem and the functions of the equipment is only part of your job. You'll have to practice many skills to maintain the equipment.

You must be a mechanic so that you can maintain, adjust, and repair fire control equipment. You must learn the principles of mechanics and how to use handtools, gages, and measuring instruments effectively.

You must be an electrician, for you'll be working with electric motors and generators, switchboards, and control devices for heavy equipments such as directors and radar sets.

You must be an electronics technician because you will repair and maintain gun and missile fire control radars, weapon direction equipments, computers and other instruments containing vacuum tube and transistor circuitry.

Maintenance and repair of fire control equipment will be only part of your job. You must become familiar with every knob, dial, and control at your battle station, for you'll be operating the equipment located there.

What kind of men make good Fire Control Technicians? What kind of mental equipment do you need to make the grade? Before the Navy approved you as a striker for FT 3, it gave you a battery of tests. Because you passed those tests and got exceptionally high marks, we know you have the ability to learn quickly, and to master a large body of technical knowledge. Also, you have mechanical aptitude; if you haven't already developed a high degree of mechanical skill, you have what it takes to acquire it.

In order to become a valuable Fire Control Technician, you'll need other things besides a sharp brain and skillful hands. You must be conscientious and completely reliable. To illustrate why these qualities are so important, let's suppose for a minute that you are aboard a destroyer in wartime, and that you have prepared a guided missile fire control system for firing. Assume that, because of carelessness, you've skipped one of the necessary adjustments, or have done it sloppily. What happens when you launch that missile at an enemy plane? Instead of riding the guidance beam to the target, the missile sets a course for the bottom of the sea. There are other things that might happen to a malfunctioning missile, but the result would be the same—the enemy escapes. The one that got away could come back and cause the death of your own ship.

But don't worry; nothing like that is going to happen to you. Why not? Because when you prepare a fire control system for firing, you'll make ALL the adjustments, and you'll make them carefully and skillfully. Before the Navy gives you the responsibility of preparing a system for firing, you'll have to prove your dependability.

KIND OF RATING

The fire control technician rating structure is:

1. a general rating at pay grades E-7 through E-9.
2. two service ratings—FTM (Missile Fire Control) and FTG (Gun Fire Control) in pay grades E-4 through E-6.

As you can see, the fire control service ratings are divided by the type of weapon being controlled. The FTG is responsible for the submarine torpedo fire control system in addition to the gun systems. Most of the chapters in this course are common to both service ratings; the following chapters are exceptions.

Chapter 2, 10, and 15 are directed at the FTG.

Chapters 3, 4, and 14 are directed at the FTM.

It is strongly recommended that you study all the chapters to obtain a complete picture of the fire control field.

NAVY ENLISTED CLASSIFICATION (NEC) CODES

The Manual of Enlisted Classifications, NavPers 15105-I, lists the specialty groups within the ratings. NEC code numbers have been assigned to indicate special training requirements within the rating. The NEC code numbers subdivide the FT rating by the types of fire control systems or equipments. There are approximately 40 NEC code numbers assigned to the FT rating. Normally, you will be assigned duty by your NEC code number to a ship with the designated system or equipment installed.

DUTIES AND RESPONSIBILITIES

Everyone wants to know what a job is like before he chooses it as his vocation. As you already know, fire control equipment is maintained, repaired, and usually operated by fire control personnel. The degree of responsibility and complexity of maintenance will depend upon your rate. Besides the occupational or professional duties, you will have certain military duties, as do all ratings in the Navy. These military duties include the manning of battle stations, watch standing, and other assignments related to the requirements for naval operations, management, and security. This course is concerned with your professional (technical) duties—NOT your military duties.

Fire Control Technicians test, inspect, clean, lubricate, and perform operational tests and adjustments of equipments comprising gun and missile fire control systems, submarine underwater fire control systems, and weapon direction systems.

In order to ensure the proper functioning of their assigned equipment, the FTs must make a detailed analysis of mechanical, electrical, and electronic failures. They must know how to perform battery and interbattery alignment.

As you increase your skill and knowledge, the Navy will add to your responsibility. Soon you will become a Fire Control Technician 3. Then you will be a leader and a teacher. You will be in a position to not only lead others, but you will be a molder of fire control strikers.

Third class is only the first step up the ladder of success. As you know, there is no limit to how far you can go in the Navy. Your division officer or weapons officer may have started his career as a fire control striker. Remember, the path to advancement is open. The rest is up to you.

As a Fire Control Technician you will have an important practical part to play in your shipboard leadership program. You will take charge of a group of strikers. This will put you in a position of leadership. You will have two responsibilities—to accomplish a mission and to take care of your men. The general principles and techniques of leadership are fully discussed in Military Requirements for PO 3 & 2, NavPers 10056-A. However, let's do a little thinking about how you can help to carry out General Order 21 on a day-to-day basis.

Assume for a moment that your mission aboard ship is to maintain a fire control system, and you have strikers to assist you. Now a big part of your job is to learn everything you can about the system and to pass on your knowledge to your men. Technical competence is a major aspect of good leadership. But being a skilled technician is not enough. You must inspire your strikers to do their work as efficiently as possible.

A national characteristic of the American fighting man is that he wants to know the reason why he is called upon to perform certain tasks. You must explain to your strikers the importance of their work and how it affects the overall fighting efficiency of your ship. Make the smallest mechanical task take on the nobility of a cause. During gunnery exercises or drills make them feel they are winning a war, not just turning knobs on equipment. Keep in mind they are the men who will fight by your side in combat. When led with courage, spirit, and intelligence, they will fight as willingly and as efficiently as any fighter in the world. But it is up to you to provide inspiration so that it will seep down to them.

To inspire your strikers, and others, you must have a strong moral character. Some of the character traits you can develop by conscientious study and practice are loyalty, integrity, and quiet self-confidence.

Loyalty is one of the most essential factors of leadership. Experienced officers and petty officers say that they would rather have a loyal man who is not an excellent worker than a disloyal man who does excellent work. Loyalty to the country, to the Navy, to your ship, to your division, to your chief, to your senior petty officer, and to the men who work with and for you—these are the prime requisites of leadership. The surest way to get the respect and loyalty of your men is to be loyal yourself.

Every time you feel the urge to criticize the handling of your ship's affairs, stop short! You are part, and an important part, of your ship. How can you expect your strikers to be loyal if you are not?

Deal with your men squarely and honestly. If you do, you will win and hold their respect. Be dependable. This mark of integrity involves keeping promises promptly. A reputation of being a "square shooter" is worth every effort on your part. Help to build this reputation early by not tolerating "gun-decking" or other methods of falsifying reports.

Good leaders have a quiet self-confidence (not an arrogant or cocky manner) based on thorough knowledge of the job and in a belief in their own ability. Confidence begets confidence. If you have confidence in yourself, you can inspire confidence in your men.

ADVANCEMENT IN RATING

Some of the rewards of advancement in rating are easy to see. You get more pay. Your job assignments become more interesting and more challenging. You are regarded with greater respect by officers and enlisted personnel. You enjoy the satisfaction of getting ahead in your chosen Navy career.

But the advantages of advancing in rating are not yours alone. The Navy also profits. Highly trained personnel are essential to the functioning of the Navy. By each advancement in rating, you increase your value to the Navy in two ways. First, you become more valuable as a technical specialist in your own rating. And second, you become more valuable as a person who can train others and thus make far-reaching contributions to the entire Navy.

HOW TO QUALIFY FOR ADVANCEMENT

What must you do to qualify for advancement in rating? The requirements may change from time to time, but usually you must:

1. Have a certain amount of time in your present grade.
2. Complete the required military and professional training courses.
3. Demonstrate your ability to perform all the PRACTICAL requirements for advancement by completing the Record of Practical Factors, NavPers 760.
4. Be recommended by your commanding officer, after the petty officers and officers supervising your work have indicated that they consider you capable of performing the duties of the next higher rate.
5. Demonstrate your KNOWLEDGE by passing a written examination on (a) military requirements and (b) professional qualifications.

Some of these general requirements may be modified in certain ways. Figure 1-1 gives a more detailed view of the requirements for advancement of active duty personnel; figure 1-2 gives this information for inactive duty personnel.

Remember that the requirements for advancement can change. Check with your division officer or training officer to be sure that you know the most recent requirements.

Advancement in rating is not automatic. After you have met all the requirements, you are ELIGIBLE for advancement. You will actually be advanced in rating only if you meet all the requirements (including making a high enough score on the written examination) and if the quotas for your rating permit your advancement.

HOW TO PREPARE FOR ADVANCEMENT

What must you do to prepare for advancement in rating? You must study the qualifications for advancement, work on the practical factors, study the required Navy Training Courses, and study other material that is required for advancement in your rating. To prepare for advancement, you will need to be familiar with (1) the Quals Manual, (2) the Record of Practical Factors, NavPers 760, (3) a NavPers publication called Training Publications for Advancement in Rating, NavPers 10052, and (4) applicable Navy Training Courses. Figure 1-3 illustrates these materials; the following sections describe them and give you some practical suggestions on how to use them in preparing for advancement.

The Quals Manual

The Manual of Qualifications for Advancement in Rating, NavPers 18068-B (with changes), gives the minimum requirements for advancement to each rate within each rating. This manual is usually called the "Quals Manual", and the qualifications themselves are often called "quals." The qualifications are of two general types: (1) military requirements, and (2) professional or technical qualifications.

MILITARY REQUIREMENTS apply to all ratings rather than to any one particular rating. Military requirements for advancement to third class and second class petty officer rates deal with military conduct, naval organization, military justice, security, watch standing, and other subjects which are required of petty officers in all ratings.

PROFESSIONAL QUALIFICATIONS are technical or professional requirements that are directly related to the work of each rating.

Both the military requirements and the professional qualifications are divided into subject matter groups; then, within each subject matter group, they are divided into PRACTICAL FACTORS and KNOWLEDGE FACTORS. Practical factors are things you must be able to DO. Knowledge factors are things you must KNOW in order to perform the duties of your rating.

The written examination you will take for advancement in rating will contain questions relating to the practical factors and the knowledge factors of both the military requirements and the professional qualifications. If you are working for advancement to second class remember that you may be examined on third class qualifications as well as on second class qualifications.

The Quals Manual is kept current by means of changes. The professional qualifications for your rating which are covered in this training course were current at the time the course was

ACTIVE DUTY ADVANCEMENT REQUIREMENTS

REQUIREMENTS *	E1 to E2	E2 to E3	E3 to E4	E4 to E5	E5 to E6	†E6 to E7	† E7 to E8	† E8 to E9
SERVICE	4 mos. service— or completion of recruit training.	6 mos. as E-2.	6 mos. as E-3.	12 mos. as E-4.	24 mos. as E-5.	36 mos. as E-6.	36 mos. as E-7. 8 of 11 years total service must be enlisted. Must be permanent appointment.	24 mos. as E-8. 10 of 13 years total service must be enlisted.
SCHOOL	Recruit Training.		Class A for PR3, DT3, PT3, AME 3, HM 3			Class B for AGCA, MUCA, MNCA.		
PRACTICAL FACTORS	Locally prepared check-offs.	Records of Practical Factors, NavPers 760, must be completed for E-3 and all PO advancements.						
PERFORMANCE TEST			Specified ratings must complete applicable performance tests before taking examinations.					
ENLISTED PERFORMANCE EVALUATION	As used by CO when approving advancement.		Counts toward performance factor credit in advancement multiple.					
EXAMINATIONS	Locally prepared tests.		Navy-wide examinations required for all PO advancements.				Navy-wide, selection board, and physical.	
NAVY TRAINING COURSE (INCLUDING MILITARY REQUIREMENTS)		Required for E-3 and all PO advancements unless waived because of school completion, but need not be repeated if identical course has already been completed. See NavPers 10052 (current edition).					Correspondence courses and recommended reading. See NavPers 10052 (current edition).	
AUTHORIZATION	Commanding Officer		U.S. Naval Examining Center			Bureau of Naval Personnel		
	TARS attached to the air program are advanced to fill vacancies and must be approved by CNARESTRA.							

* All advancements require commanding officer's recommendation.
† 2 years obligated service required.

Figure 1-1.—Active duty advancement requirements.

INACTIVE DUTY ADVANCEMENT REQUIREMENTS

REQUIREMENTS *		E1 to E2	E2 to E3	E3 to E4	E4 to E5	E5 to E6	E6 to E7	E8	E9
	FOR THESE DRILLS PER YEAR								
TOTAL TIME IN GRADE	48	6 mos.	6 mos.	15 mos.	18 mos.	24 mos.	36 mos.	36 mos.	24 mos.
	24	9 mos.	9 mos.	15 mos.	18 mos.	24 mos.	36 mos.	36 mos.	24 mos.
	NON-DRILLING	12 mos.	24 mos.	24 mos.	36 mos.	48 mos.	48 mos.		
TOTAL TRAINING DUTY IN GRADE †	48	14 days	14 days	14 days	14 days	28 days	42 days	42 days	28 days
	24	14 days	14 days	14 days	14 days	28 days	42 days	42 days	28 days
	NON-DRILLING	None	None	14 days	14 days	28 days	28 days		
PERFORMANCE TESTS				Specified ratings must complete applicable performance tests before taking examination.					
DRILL PARTICIPATION		Satisfactory participation as a member of a drill unit.							
PRACTICAL FACTORS (INCLUDING MILITARY REQUIREMENTS)		Record of Practical Factors, NavPers 760, must be completed for all advancements.							
NAVY TRAINING COURSE (INCLUDING MILITARY REQUIREMENTS)		Completion of applicable course or courses must be entered in service record.							
EXAMINATION		Standard exams are used where available, otherwise locally prepared exams are used.						Standard EXAM, Selection Board, and Physical.	
AUTHORIZATION		District commandant or CNARESTRA					Bureau of Naval Personnel		

* Recommendation by commanding officer required for all advancements.

† Active duty periods may be substituted for training duty.

Figure 1-2.—Inactive duty advancement requirements.

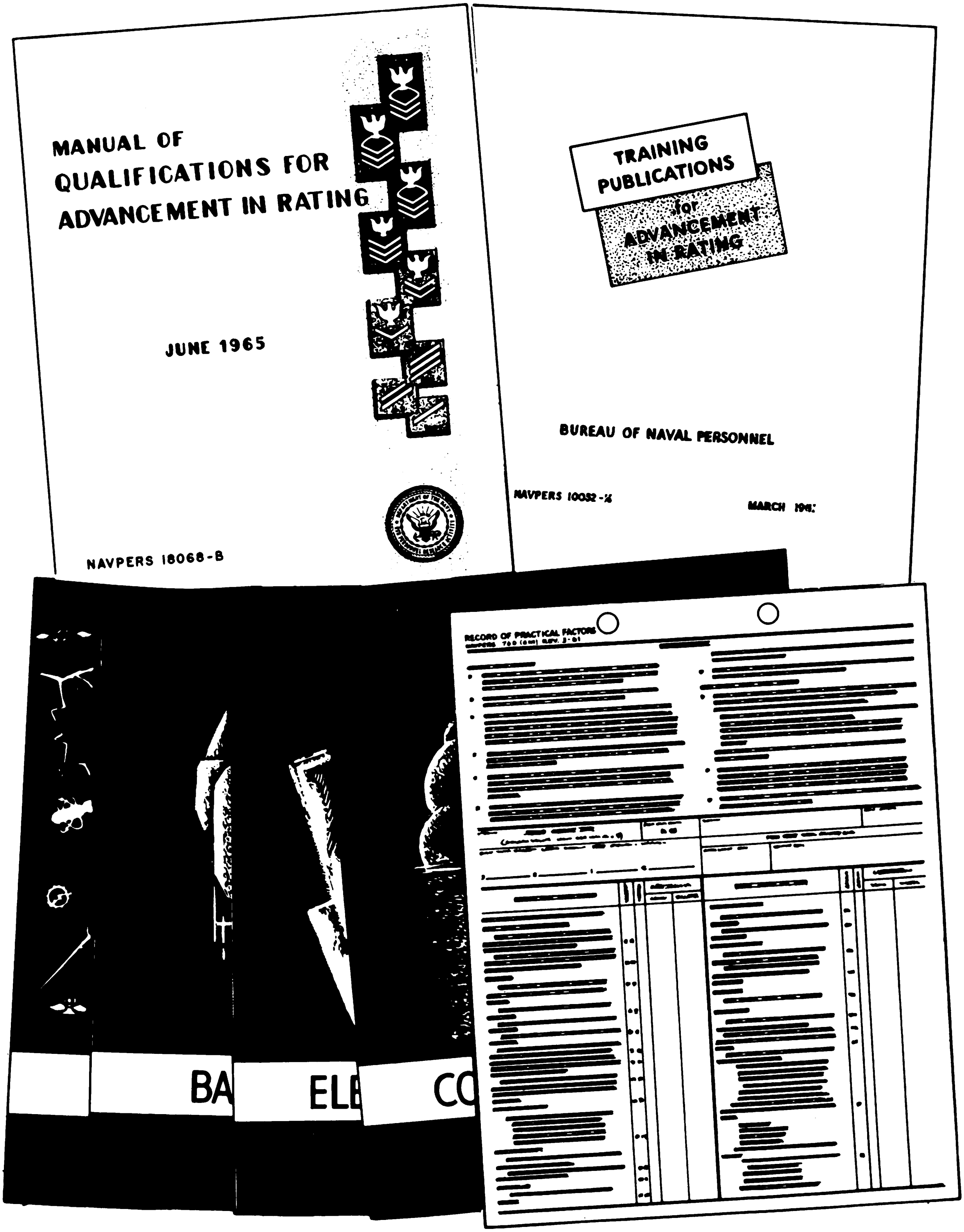

Figure 1-3.—Materials used in preparing for advancement.

printed. By the time you are studying this course, however, the quals for your rating may have been changed. Never trust any set of quals until you have checked it against an UP-TO-DATE copy in the Quals Manual.

Record of Practical Factors

Before you can take the servicewide examination for advancement in rating, there must be an entry in your service record to show that you have qualified in the practical factors of both the military requirements and the professional qualifications. A special form known as the RECORD OF PRACTICAL FACTORS, NavPers 760, is used to keep a record of your practical factor qualifications. This form is available for each rating. The form lists all practical factors, both military and professional. As you demonstrate your ability to perform each practical factor, appropriate entries are made in the DATE and INITIALS columns.

Changes are made periodically to the Manual of Qualifications for Advancement in Rating, and revised forms of NavPers 760 are provided when necessary. Extra space is allowed on the Record of Practical Factors for entering additional practical factors as they are published in changes to the Quals Manual. The Record of Practical Factors also provides space for recording demonstrated proficiency in skills which are within the general scope of the rating but which are not identified as minimum qualifications for advancement.

If you are transferred before you qualify in all practical factors, the NavPers 760 form should be forwarded with your service record to your next duty station. You can save yourself a lot of trouble by making sure that this form is actually inserted in your service record before you are transferred. If the form is not in your service record, you may be required to start all over again and requalify in the practical factors which have already been checked off.

NavPers 10052

Training Publications for Advancement in Rating, NavPers 10052 (revised), is a very important publication for anyone preparing for advancement in rating. This bibliography lists required and recommended Navy Training Courses and other reference material to be used by personnel working for advancement in rating. NavPers 10052 is revised and issued once each year by the Bureau of Naval Personnel. Each revised edition is identified by a letter following the NavPers number. When using this publication, be SURE that you have the most recent edition.

If extensive changes in qualifications occur in any rating between the annual revisions of NavPers 10052, a supplementary list of study material may be issued in the form of a BuPers Notice. When you are preparing for advancement, check to see whether changes have been made in the qualifications for your rating. If changes have been made, see if a BuPers Notice has been issued to supplement NavPers 10052 for your rating.

The required and recommended references are listed by rate level in NavPers 10052. If you are working for advancement to third class, study the material that is listed for third class. If you are working for advancement to second class, study the material that is listed for second class; but remember that you are also responsible for the references listed at the third class level.

In using NavPers 10052, you will notice that some Navy Training Courses are marked with an asterisk (*). Any course marked in this way is MANDATORY—that is, it must be completed at the indicated rate level before you can be eligible to take the servicewide examination for advancement in rating. Each mandatory course may be completed by (1) passing the appropriate enlisted correspondence course that is based on the mandatory training course; (2) passing locally prepared tests based on the information given in the training course; or (3) in some cases, successfully completing an appropriate Class A school.

Do not overlook the section of NavPers 10052 which lists the required and recommended references relating to the military requirements for advancement. Personnel of ALL ratings must complete the mandatory military requirements training course for the appropriate rate level before they can be eligible to advance in rating.

The references in NavPers 10052 which are recommended but not mandatory should also be studied carefully. ALL references listed in NavPers 10052 may be used as source material for the written examinations, at the appropriate rate levels.

Navy Training Courses

There are two general types of Navy Training Courses. RATING COURSES (such as this one) are prepared for most enlisted ratings. A rating training course gives information that is directly related to the professional qualifications of ONE rating. SUBJECT MATTER COURSES or BASIC COURSES give information that applies to more than one rating.

Navy Training Courses are revised from time to time to keep them up to date technically. The revision of a Navy Training Course is identified by a letter following the NavPers number. You can tell whether any particular copy of a Navy Training Course is the latest edition by checking the NavPers number and the letter following this number in the most recent edition of List of Training Manuals and Correspondence Courses, NavPers 10061. (NavPers 10061 is actually a catalog that lists all current training courses and correspondence courses; you will find this catalog useful in planning your study program.)

Navy Training Courses are designed to help you prepare for advancement in rating. The following suggestions may help you to make the best use of this course and other Navy training publications when you are preparing for advancement in rating.

1. Study the military requirements and the professional qualifications for your rating before you study the training course, and refer to the quals frequently as you study. Remember, you are studying the training course primarily in order to meet these quals.

2. Set up a regular study plan. It will probably be easier for you to stick to a schedule if you can plan to study at the same time each day. If possible, schedule your studying for a time of day when you will not have too many interruptions or distractions.

3. Before you begin to study any part of the training course intensively, become familiar with the entire book. Read the preface and the table of contents. Check through the index. Look at the appendixes. Thumb through the book without any particular plan, looking at the illustrations and reading bits here and there as you see things that interest you.

4. Look at the training course in more detail, to see how it is organized. Look at the table of contents again. Then, chapter by chapter, read the introduction, the headings, and the subheadings. This will give you a pretty clear picture of the scope and content of the book. As you look through the book in this way, ask yourself some questions: What do I need to learn about this? What do I already know about this? How is this information related to information given in other chapters? How is this information related to the qualifications for advancement in rating?

5. When you have a general idea of what is in the training course and how it is organized, fill in the details by intensive study. In each study period, try to cover a complete unit—it may be a chapter, a section of a chapter, or a subsection. The amount of material that you can cover at one time will vary. If you know the subject well, or if the material is easy, you can cover quite a lot at one time. Difficult or unfamiliar material will require more study time.

6. In studying any one unit—chapter, section, or subsection—write down the questions that occur to you. Many people find it helpful to make a written outline of the unit as they study, or at least to write down the most important ideas.

7. As you study, relate the information in the training course to the knowledge you already have. When you read about a process, a skill, or a situation, try to see how this information ties in with your own past experience.

8. When you have finished studying a unit, take time out to see what you have learned. Look back over your notes and questions. Maybe some of your questions have been answered, but perhaps you still have some that are not answered. Without looking at the training course, write down the main ideas that you have gotten from studying this unit. Don't just quote the book. If you can't give these ideas in your own words, the chances are that you have not really mastered the information.

9. Use Enlisted Correspondence Courses whenever you can. The correspondence courses are based on Navy Training Courses or on other appropriate texts. As mentioned before, completion of a mandatory Navy Training Course can be accomplished by passing an Enlisted Correspondence Course based on the Navy Training Course. You will probably find it helpful to take other correspondence courses, as well as those based on mandatory training courses. Taking a correspondence course helps you to master the information given in the training course, and also helps you see how much you have learned.

10. Think of your future as you study Navy Training Courses. You are working for advancement to third class or second class right now, but someday you will be working toward higher rates. Anything extra that you can learn now will help you both now and later.

SOURCES OF INFORMATION

One of the most useful things you can learn about a subject is how to find out more about it. No single publication can give you all the information you need to perform the duties of your rating. You should learn where to look for accurate, authoritative, up-to-date information on all subjects related to the military requirements for advancement and the professional qualifications of your rating.

Some of the publications described here are subject to change or revision from time to time—some at regular intervals, others as the need arises. When using any publication that is subject to change or revision, be sure that you have the latest edition. When using any publication that is kept current by means of changes, be sure you have a copy in which all official changes have been made. Studying canceled or obsolete information will not help you to do your work or to advance in rating; it is likely to be a waste of time, and may even be seriously misleading.

NAVY TRAINING COURSES

Before you study this book you should become thoroughly familiar with the appropriate subject matter contained in the following publications.

Mathematics, Volume 1, NavPers 10069-B
Mathematics, Volume 2, NavPers 10070-A
Basic Electricity, NavPers 10086-A
Basic Electronics, NavPers 10087
Fire Control Fundamentals, NavPers 91900
Fire Control Radar Fundamentals, NavPers 91901
Weapons Systems Fundamentals, Volume 1, 2, and 3 OP 3000

OTHER SOURCES

ORDNANCE PAMPHLETS (OP).—These books are issued by the former Bureau of Ordnance, now the Bureau of Naval Weapons (BuWeps). The list of all OPs published is OP O. An OP on naval weapons systems is OP 3000, Volume 2, Weapons Systems Fundamentals. Be sure you have the latest revision or changes.

ORDNANCE DATA (NAVORD OD).—These pamphlets generally contain reports of ordnance inspection and test data, and ordnance equipment lists. ODs are indexed in OP O. An OD referred to in this text is OD 3000, Lubrication of Ordnance Equipment.

The United States Armed Forces Institute (USAFI) provides opportunities for military personnel to continue their education while they are on active duty with the Armed Forces of the United States. See your education officer about the details of taking courses. If there are enough interested students aboard ship (or on the base) a group study course can be arranged.

Training films are a valuable source of information on many technical subjects. A selected list of training films that may be useful to you is given in appendix I of this training course. Other unclassified films that may be of interest to you are listed in the United States Navy Film Catalog, NavPers 10000 (Revised), confidential training films that may be of interest to you are listed in the confidential film catalog NavPers 10001-A.

TRAINING FILMS

Training films available to naval personnel are a valuable source of supplementary information of many technical subjects. A selected list of training films that may be useful to you is given in appendix I of this training course. Other films that may be of interest are listed in the United States Navy Film Catalog, NavPers 10000 (revised).

When selecting a film, note its date of issue listed in the film catalog.

As you know, procedures sometimes change rapidly. Thus some films become obsolete rapidly. If a film is obsolete only in part, it may sometimes be shown effectively, if before or during its showing you carefully point out to trainees the procedures that have changed. For this reason if you are showing a film to train other personnel, take a look at it in advance if possible so that you may spot material that may have become obsolete and verify current procedures by looking them up in an applicable source before the formal showing.

CHAPTER 2

THE GUN FIRE CONTROL PROBLEM

INTRODUCTION

The central theme of this chapter is that there is basically only one fire control problem. This is supported by the definition which states that fire control is the technique of delivering effective fire so as to damage or destroy a selected target. It may appear to you that this definition is oversimplified, and of little use to us. Since the type of weapon is not specified, gun, guided missile, rocket, and torpedo fire are included in the definition. Furthermore, the circumstances surrounding the firing and the target are not described; hence the weapon may be fired from any suitable platform, which may or may not be located on a ship. The target may be in the air, on the surface, or underwater. The weapon platform and the target may be stationary or moving. The word technique in the definition implies the method used to control and direct the fire, and is not very descriptive.

The value of the definition is that it reduces the fire control problem to this basic question: how can a ship, underway or dead-in-the-water, destroy a stationary or moving target? The first step in problem solving is to state the problem so as to determine what is known and what is required. We will state the problem as presented by a surface target, and then associate the problem with a gun fire control system. Once the basic problem is understood we can deal with modification as required by an air target and with the techniques of its solution. From this vantage point we can proceed in an orderly fashion to a representative gun fire control system for air targets.

Since by definition there is one basic fire control problem, it is logical to assume that many fundamental elements are common to all the variations of the problem. The word element as used here refers to a basic quantity or factor. Therefore much of the material in this chapter is applicable with little or no change to the missile fire control problem. To avoid repetition, the background theory of the common elements will not be covered in the chapter on the missile fire control problem. We will simply refer back to this chapter when necessary. Consequently, the FTM should not skip this chapter.

THE SCIENCE OF BALLISTICS

In this section we will study all the various forces, controllable and uncontrollable, that govern the movements of projectiles. At present we will consider only the gun projectile. But the forces that affect the flight of a gun projectile have a similar effect on a guided missile. The study of ballistics is normally divided into two branches, called Interior and Exterior Ballistics. The study of interior ballistics is primarily concerned with the movement of projectiles inside the gun. Exterior ballistics is concerned with the motion of projectiles after leaving the bore of the gun.

The curved path a projectile travels in passing from the gun muzzle to the first point of impact is called its trajectory. The curvature of the trajectory is the result of forces acting on the projectile in flight. If it were not for these forces, the projectile would travel in a straight line. Obviously, knowledge of the trajectory a projectile will take is necessary to position a gun correctly.

INTERIOR BALLISTICS

The study of interior ballistics deals with the mechanical, ballistic, and service condition of the gun. A satisfactory gun must meet several requirements. It must withstand the pressures developed by the propelling charge. It must discharge the projectile at the desired velocity. (The projectile's velocity at the instant it leaves the muzzle is called either muzzle velocity or initial velocity.) Finally, the gun must meet the service specifications as to ease of breech and loading operations.

We must know the initial velocity of the projectile in order to predict its trajectory. Initial velocity is determined by the gun, the projectile, and the propelling charge. Under controlled conditions a fixed combination of these factors will produce the same initial velocity at each firing. The controlled conditions are: (1) a new gun with no wear and (2) a standard projectile and propelling charge. We will briefly explain here the factors affecting initial velocity of a projectile. We will discuss them in detail in a later volume in this series of training courses.

Let's start with the gun. Basically, a gun is a tube capable of withstanding the explosion of a powder charge (propellant), and of controlling the propelling force so as to discharge the projectile at high velocity in a desired direction. Figure 2-1 shows a cutaway view of a gun. The barrel is a tube which is sealed at one end by the breech mechanism after the projectile and powder charge have been loaded into the gun chamber. The projectile engages the gun bore and seals the other end of the chamber. When the powder charge is ignited, it produces gas at extremely high pressure. This pressure forces the projectile through the gun bore. A soft metal band, called the rotating band, on the projectile (fig. 2-2) is enmeshed with the rifling in the gun bore (fig. 2-3). A twist in the rifling as it extends down the bore causes the projectile to rotate as it passes through the bore. The rotary motion causes the projectile to spin in flight. This spinning motion keeps the projectile from tumbling end-for-end, and makes it trajectory predictable. We will come back to projectile spin when we discuss exterior ballistics.

The powder charge is the source of the gas pressure which is the prime mover of the projectile. But before we discuss gun powder in detail, let's take a quick look at explosives in general. There are two broad classifications of explosives. HIGH EXPLOSIVES are used as bursting charges in warheads and projectiles; LOW or PROGRESSIVE EXPLOSIVES are used as propellants in guns and guided missiles. The major difference between the two classes is the rate at which they deliver energy. Energy is released when the explosive burns or detonates, and turns to gas. The class of an explosive is determined by how fast it becomes a gas. The term detonation is used to describe an almost instantaneous explosive reaction. Low explosives burn; high explosives detonate.

Our interest is in progressive explosives used as propellants. Navy guns use granulated smokeless powder which does not detonate, but burns in a measurable length of time. The time is in the order of a fraction of a second, resulting in a gradual evolution of gases.

Experiments have shown that grains of smokeless powder burn in parallel layers at a uniform rate. As each layer of molecules burns, the next layer is exposed to combustion. This continues until the grain is consumed. The combustion occurs entirely on the exposed surfaces of the grain. Hence by varying the amount of surface exposed to combustion, the powder's burning rate and consequently its rate of energy release can be varied. The smokeless powder grains are cylindrical, and perforated from end to end. The size of the grain and the number of holes in it can be varied to obtain the desired burning rate.

The potential energy of the powder is another important aspect of internal ballistics. It is pertinent to observe that the potential energy of

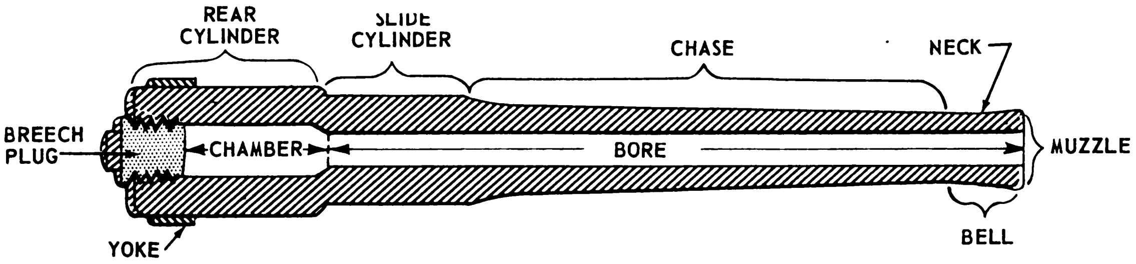

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Figure 2-1.—Cross section of a gun.

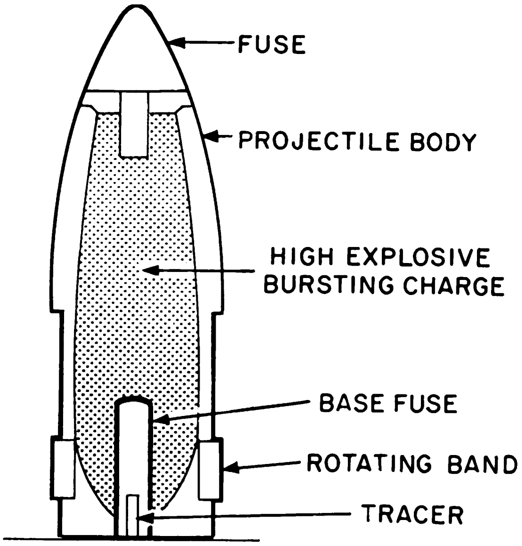

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Figure 2-2.—Projectile rotating band.

gunpowder is relatively low when compared with our common fuels, such as coal, oil, and gasoline. However, powder has such a tremendous RATE OF DELIVERY OF ENERGY that one would not consider offhand a comparison of explosives and fuels with regard to their "power" potential. The potential energy stored in a pound of smokeless powder (nitrocellulose) has been determined experimentally to be 560 foot-tons.

The powder must be selected to "fit the gun". In the first place, the powder must NOT burn so rapidly that complete combustion will occur before the projectile has started down the bore. If this were to happen, dangerous chamber pressures would build up causing probable violent rupture of the gun. On the other hand, the powder should have completely burned before the projectile actually leaves the muzzle of the gun in order that the total energy of the powder can be used. Obviously, the Fire Control Technician will not make this selection of powder, but the knowledge gives him reason to ensure that computer corrections are made with a change in the type of ammunition used.

Erosion of the gun bore is caused by the intense heating of a thin layer of metal at the surface of the bore, and by the rush of hot gases over this surface. Erosion results in a gradual enlargement of the bore. It begins at the rear of the bore and extends farther down the bore as the gun is used. The lands are eroded about twice as fast as the grooves (fig. 2-3).

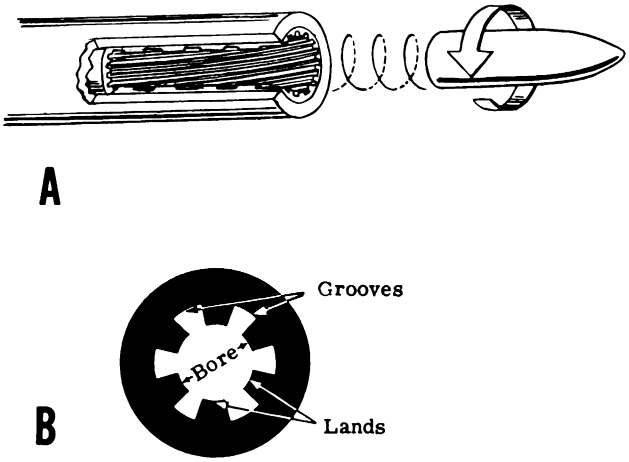
The service life of the gun is determined by the number of service rounds that may be fired through it before it loses its accuracy. If erosion did not take place within the gun, the gun's service life would be spectacularly prolonged.

All the factors previously described affect the initial velocity, i.e., the speed of the projectile at the time it leaves the muzzle of the gun. We will have more to say about initial velocity in the next section, because it is one value that is common to both interior and exterior ballistics.

EXTERIOR BALLISTICS

Exterior ballistics starts with a projectile traveling at a known speed and in a known direction. This direction, called the LINE OF FIRE, for all practical purposes coincides with the center line or axis of the gun bore. Once the projectile leaves the gun, you have no further control over its trajectory. Forces of nature act on the projectile in flight to alter the trajectory. Therefore, to hit a target it is necessary to know these forces and to compensate for their effects by changing the gun's position before firing. For example, if you know that the projectile is going to curve to the right, you will train the gun to the left. If you know the projectile is going to curve downward, you will elevate the gun.

You shuld realize that the ultimate purpose of all the fire control gear—directors, radars,



84.143

Figure 2-3.—A. Cross section of bore; B. End view of bore.

synchros, servos, computers, and power drives—is to find the right position for the gun barrel to make the projectile fall where you want it to, and to put the gun in that position.

In our discussion of exterior ballistics we will not specify a particular gun, or type of projectile, or initial velocity. The factors involved are physical, hence natural, and their effects are felt in all gun-projectile-velocity combinations. Two of these factors that are always present are the pull of gravity and the resistance of the atmosphere. Their effects on a trajectory can best be seen by showing a theoretical trajectory in which they are absent. This will have to be a hypothetical case located in outer space and representing the simplest fire control problem.

Hypothetical Case

If you were far enough in outer space and picked up a projectile and then let go of it, the projectile would stay where you put it. Out in space objects have little or no weight—there are no bodies close enough to exert an appreciable gravitational pull. Since there is no atmosphere in outer space there is no air resistance to hinder the flight of a projectile.

So how are you going to lay the gun? The answer is provided by one of the fundamental laws of physics—Newton's first law of motion. This law states that any moving body will continue to move in a straight line at the same speed until something interferes with it. When the projectile shoots out the muzzle of your "space" gun at a speed of 2700 feet per second, there is nothing to interfere with it. It will simply continue to travel at this speed along the line of fire indefinitely or until it hits something.

That would make fire control pretty easy. You would not have to worry about the many other factors that are involved in laying a gun on a ship on the surface of the earth. You would just sight the gun barrel at the target and press the firing key. If the enemy were on the line of the gun bore axis and stayed there, he would be hit no matter how far away he might be.

Problem of Gravity

But let's get down to earth where things are not so easy. Here, if you lift a projectile and then let go of it, it will fall to earth. This of course is due to the force of gravity. Gravity is always an attracting force, acting perpendicular to the surface of the earth, which tends to pull all objects towards the earth. (Newton's apple fell down, not up.)

A falling body, generally speaking, falls faster and faster the longer it falls. In each second of fall, an object increases its speed by about 32.2 feet per second. (The acceleration due to gravity is usually called g.)

Effect of Gravity in a Vacuum

Suppose you could line up the axis of a gun bore in a vacuum and fire it straight at a target at zero elevation (fig. 2-4). As before, the projectile will continue to travel in the same direction and at the same speed unless something interferes with it. But now something does—gravity.

As soon as the projectile leaves the gun it starts to fall, just like any other object. The projectile, however, is traveling forward and falling at the same time. The projectile has two forces acting on it—the momentum imparted by the forward thrust of the gun's propulsion system, and the pull of gravity. The path of the projectile as a result of these two forces is a curved trajectory, as shown in the figure.

The forward momentum of the projectile tends to keep the trajectory a straight line in accord with Newton's first law of motion. Gravity, however, starts the projectile falling. The constant pull of gravity causes the falling motion to accelerate and the downward slope of the trajectory to increase.

If the projectile is going to curve downward when you fire the gun, you must elevate the gun. But the question is, how much? Suppose you elevate the gun above the horizon by some angle, as shown in figure 2-5. This angle, the gun elevation above the horizontal, is known in ballistics as the ANGLE OF DEPARTURE. In ballistics the earth's surface is assumed to be flat, and it is used as the horizontal reference plane.

The projectile's momentum will tend to keep the trajectory in the line of fire. Since

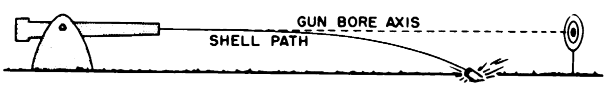


Figure 2-4.—Projectile motions. 12.1

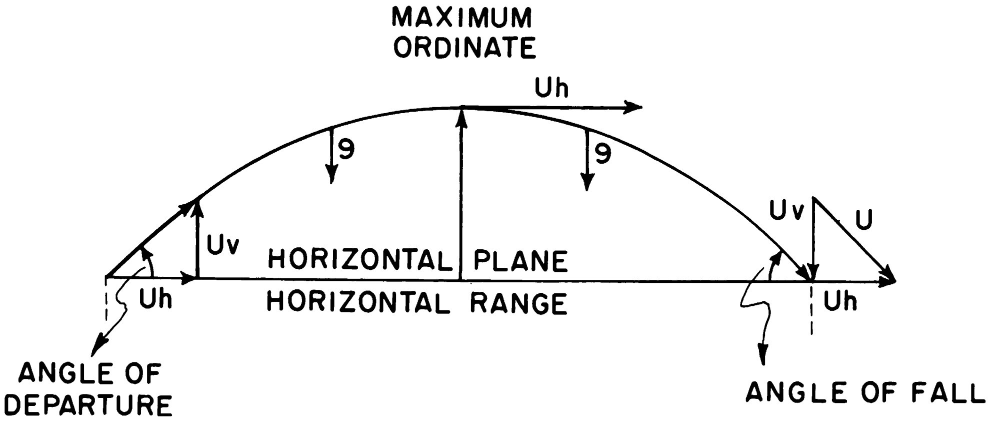


Figure 2-5.—Vacuum trajectory.

the angle of departure is elevated above the horizontal, the projectile's momentum can be divided into horizontal and vertical components. The horizontal component of the projectile's momentum causes the projectile to travel across the surface of the earth. The vertical component causes the projectile to ascend above the surface of the earth.

The percentage of the projectile's momentum contained in each of the components is a function of the angle of departure. We will consider this factor later. The percentages for the angle in the figure are indicated by the length of the vectors. The vector representing the total momentum is labeled U, while the horizontal component is Uh and the vertical component Uv.

Gravity begins to act on the projectile the instant it leaves the gun, and tends to pull it out of the line of fire towards the earth. Initially, however, the vertical component, Uv, is greater by far than the pull of gravity (g) and the projectile's trajectory will be upward. But because of the constant gravitational pull, Uv will diminish as the projectile climbs. Since g is acting on the projectile continuously, the downward deviation from the line of fire becomes greater with the passage of time.

Eventually g will become equal to the diminishing Uv. At this time the projectile will stop climbing; it is then at the highest point, called the maximum ordinate, of its trajectory. From this point it begins to fall. The projectile, as it falls, is accelerated by g. Since g is constant, it will add the same amount of velocity to the projectile in the falling portion of the flight as is subtracted in the climbing portion of the flight. Consequently the velocity at which the projectile strikes the earth will equal the initial velocity.

The curvature of the trajectory is the reaction to the three vectors Uh, Uv, and g. The horizontal component, Uh, is not affected by gravity and so is constant throughout the trajectory. Remember that we are in a vacuum, and that gravity is the only retarding factor. Since Uh is constant the projectile will travel an equal distance in the horizontal plane in each second of the time of flight. This fact, coupled with the fact that g also is constant, means that the maximum ordinate will be in the exact center of the trajectory, and that the two halves of the trajectory's curve are identical. Hence the angle at which the projectile lands, called the ANGLE OF FALL, is equal to the angle of departure. The shape of the trajectory is a curve known in geometry as a parabola.

The distance from the gun to the point where the projectile hits the ground is called HORIZONTAL RANGE. The range obtained in a vacuum is determined by the initial velocity of the projectile and the angle of departure of the gun. For a given angle of departure an increase in initial velocity will increase range, while a decrease in initial velocity will decrease range. This is obvious, but the variation in range due to a change in the angle of departure needs an explanation.

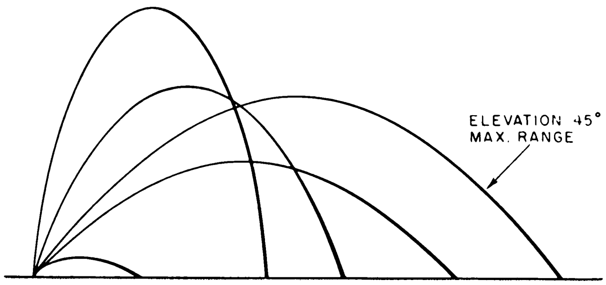
It can be seen from figure 2-5 that the vectors Uv and Uh vary as functions (sine and cosine, respectively) of the angle of departure. As the angle is increased, the vertical component Uv will increase. Consequently it will take a longer time for gravity to stop the upward motion of the projectile and to pull the projectile back to earth. Hence the maximum ordinate will increase as the angle increases, and the time of flight will become longer.

The horizontal component, Uh, will decrease with an increase in the angle of departure. However, at angles of departure between 0 and 45 degrees an increase in the angle will result in an increase in the horizontal range, due to the longer time of flight. Maximum horizontal range in a vacuum would be obtained at an angle of departure of 45 degrees. Typical trajectories in a vacuum are shown in figure 2-6. Note in the figure that at angles of departure above 45°, the maximum ordinate is higher and the horizontal range is shorter than at 45 degrees. At high angles most of the projectile's momentum is in the vertical plane, and although the time of flight becomes longer, the reduction in the horizontal component of the projectile's momentum will shorten the horizontal range.

High angle fire is not often used in surface fire. One example of its use is given in this chapter when reverse slope fire is discussed in the gunfire support section. High angle fire, with its high maximum ordinate, is extremely important in antiaircraft (AA) gun fire.

We can summarize the characteristics of a vacuum trajectory in earth's gravity field as follows:

1. Striking velocity equals initial velocity.
2. Angle of fall equals angle of departure.
3. Maximum ordinate is in the center of the trajectory.
4. The projectile travels a symmetrical curve called a parabola.
5. Maximum range is obtained with a 45° angle of departure.



12.3

Figure 2-6.—Typical vacuum trajectories for different angles of departure.

A comparison of the hypothetical space shot and the vacuum trajectories will indicate the affect of gravity. You will never fire in a vacuum, and therefore these trajectories are hypothetical. Now we will add the air in the earth's atmosphere and arrive at actual firing conditions.

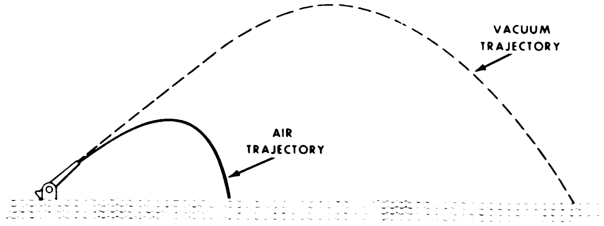
Effects of Air

When the projectile is traveling through air, it takes a different path from the one it would follow in a vacuum.

Air resists the motion of any body passing through it. That is, when any body is moving through the air, the air will set up a force pushing backward in the line of motion of the body. This force keeps slowing the movement of the body, and a certain amount of speed is lost during each second of its flight.

With a little thought you can see what air resistance does to the shape of a vacuum trajectory. When first fired the projectile has the greater momentum, hence the greater resistance to any change of its motion. The longer the projectile travels through the air, the slower it goes. As you know, the horizontal component of the projectile's momentum or velocity is unaffected by gravity. Consequently the horizontal distance traveled is smaller for each consecutive second of flight. Naturally the vertical component of the projectile's velocity is also affected by air resistance. The vertical component, however, is accelerated by gravity during the descent of the projectile. Therefore the air trajectory will be greatly modified from the vacuum trajectory at its far end, where the horizontal velocity is greatly reduced.

In figure 2-7 you can see how the trajectory of a projectile fired in air differs from that of a projectile fired at the same angle of departure



12.4

Figure 2-7.—Comparison of vacuum and air trajectories for same angle of elevation.

in a vacuum. Notice the steepness of the descending curve in the air trajectory. And note that the maximum ordinate is not at the middle of the trajectory, but is nearer the point of impact than it is to the gun. Notice also that the range of the projectile in air is much less than its range in a vacuum.

In order to give a projectile the same range in air that you would get in a vacuum, you would have to elevate the gun much farther, as shown in figure 2-8. And if the elevation were already set for maximum range (45°), an equal range could not be achieved.

A peculiar thing about air resistance is that it increases rapidly as the speed of the body increases. Roughly, when the speed doubles, the retardation of the projectile becomes more than four times as great. Thus, if a projectile traveling at 1000 ft/sec were retarded 100 ft/sec every second, a projectile traveling 2000 ft/sec might be slowed as much as 400 ft/sec every second.

The DENSITY of the air determines the amount of resistance of the air to the projectile. Dense air will slow the travel of a projectile more than thin air, and this complicates the problem quite a bit. Air density depends on temperature and barometric pressure and these values are changing all the time. Moreover, the density is less at higher altitudes than it is at sea level. Since the trajectory rises high into the air for a long-range shot, the projectile will be retarded less during each second that it is in the upper portion of the trajectory than when it is at the low points.

Another thing that affects the shape of the trajectory is the WEIGHT of the projectile. The heavier the projectile, fired at the same initial velocity, the more momentum the projectile has and the less its trajectory is affected by air resistance.

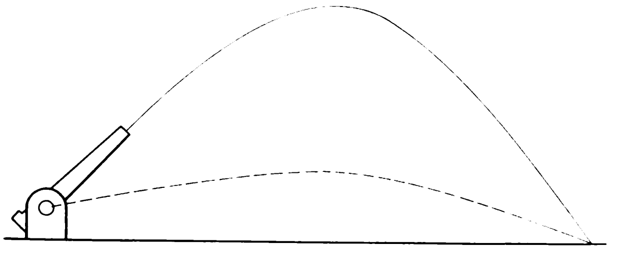

12.5

Figure 2-8.—The gun must be elevated farther in air.

The SHAPE of the projectile also makes a difference. Obviously, the bigger around the projectile is, the more air will push against it. A pointed nose makes it easier for the projectile to push its way through the air and reduces resistance. Boattailing or tapering the after end of the projectile reduces the drag resulting from air turbulence behind the projectile, which also reduces resistance.

The effect on the air resistance resulting from the shape of the projectile is expressed by a quantity called the COEFFICIENT OF FORM. The data for such a drag coefficient or resistance curve are available from measurements obtained by actual experimental firings of the standard projectile at the Naval Weapons Laboratory, formerly call the Naval Proving Ground.

Finding the Range of a Projectile

You have learned that when a stationary gun fires in air, the range attained will depend on the following things:

1. Initial velocity
2. Elevation above the horizontal
3. Density of the air
4. Weight of the projectile
5. Shape of the projectile

It is possible to work out mathematically the shape of the air trajectory for different values of the above quantities. The computation is quite difficult, and is performed by men familiar with higher mathematics. When the calculation has been made, it is possible to work out tables giving the range, time of flight, and maximum ordinate of the trajectory for different values of the above quantities.

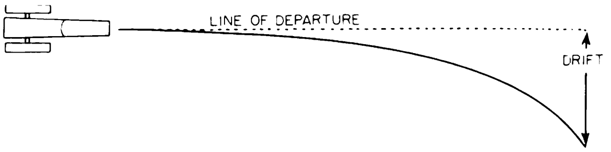
A STANDARD ATMOSPHERE is arbitrarily assumed. This standard assumes a temperature at sea level of 59° F., and a barometric pressure of 29.53 inches. The standard also assumes that the air density decreases, according to a standard formula, as you go higher in the air.

The next step is to insert the values of a particular gun, projectile, and velocity combination into the calculations. For example, the 5"/38 gun is designed to have an initial velocity of 2600 ft/sec, and the weight of the standard projectile is 54 pounds. The shape of the standard projectile is entered into the calculation by the value of the coefficient of form.

Drift

Naval guns are rifled to give a spinning motion to the projectile. The spinning projectile assumes the properties of a gyroscope (gyroscopes are covered in a later chapter.) The gyroscopic action tends to keep the projectile pointed along the trajectory, and prevents it from tumbling. This makes the projectile almost rigid in its trajectory, and ensures that it will land point first. It is this property of rigidity which makes the trajectory predictable.

In addition to its useful effect, gyroscopic action causes the harmful effect of drift. Figure 2-9 shows the effect of drift on the projectile while in flight. Notice that the drift increases with range; but do not confuse this motion with the movement caused by wind. Drift is always to the right in any gun with right-hand rifling which gives a clockwise spin to the projectile.



12.7

Figure 2-9.—Effect of drift.

The exact causes of drift are complicated, and beyond this discussion. It is enough to say that drift is the result of the interaction of gravity and air resistance on the spinning projectile. Fortunately a projectile drifts by a definite amount which has been determined by experiments and tabulations.

To compensate for projectile drift to the right, you must train the gun to the left. The question is how much? As you can see in the figure, the overall effect of drift is a linear deviation of the projectile. The gun trains in an angular motion so we must convert the linear value to an angular value. We have a very handy quantity called a MIL which will do this for us at any range. A mil is the angle which will cause a deflection equal to 1/1000 the radius of a circle. The angular value of the mil is constant (3.43 minutes of arc) but the radius of a circle is variable. We consider range to be the radius of the circle. Hence 1 mil is equal to 1 yard at a range of 1000 yards. If the range is 10,000 yards, then 1 mil equals 10 yards.

Earth's Rotation

Thus far in your study of the problem of hitting a fixed target from a fixed gun you have learned of the effects on the flight of a projectile of initial velocity, gravity, air resistance, drift, and wind. These are the most important factors which determine the projectile's trajectory, and they require the largest corrections to elevation and train settings. There is one other factor which affects the projectile's flight and which should be mentioned. This is the effect of the earth's rotation or, as it is sometimes called, the Coriolis force.

In our discussion so far we have assumed that the earth is flat and does not rotate. For ranges up to about 20,000 yards or so, such an assumption does not cause any serious effect on the flight of a projectile. At longer ranges, however, the Coriolis force has a serious effect.

Any object that moves in any direction above the surface of the earth tends to turn toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere. This deflection to the right or left is an effect of two motions: the rotation of the earth and the movement of the object in relation to the earth's surface.

Suppose that you had a gun at the North Pole (see fig. 2-10) which could fire a projectile far enough to reach a target fixed at the equator. Because the earth spins on an axis through the North Pole the gun would be stationary. But the target would be moving at a velocity of about 1000 miles per hour, since a fixed point on the equator has that velocity due to the earth's rotation. If you aimed the gun at the target and fired, the target would move several miles during the time the projectile is in flight, and the projectile would land where the target had been at the instant of firing. In order to score a hit it is necessary to "lead" the target, that is, train the gun on the point to which the target will have moved during the projectile's flight. Projectile and target will arrive at this point at the same time.

A correction is made for the error introduced by the earth's rotation only on guns larger than 5-inch, since the error is negligible in smaller guns.

RANGE TABLES

So far we have discussed the effects of the earth's environment on the trajectory of a

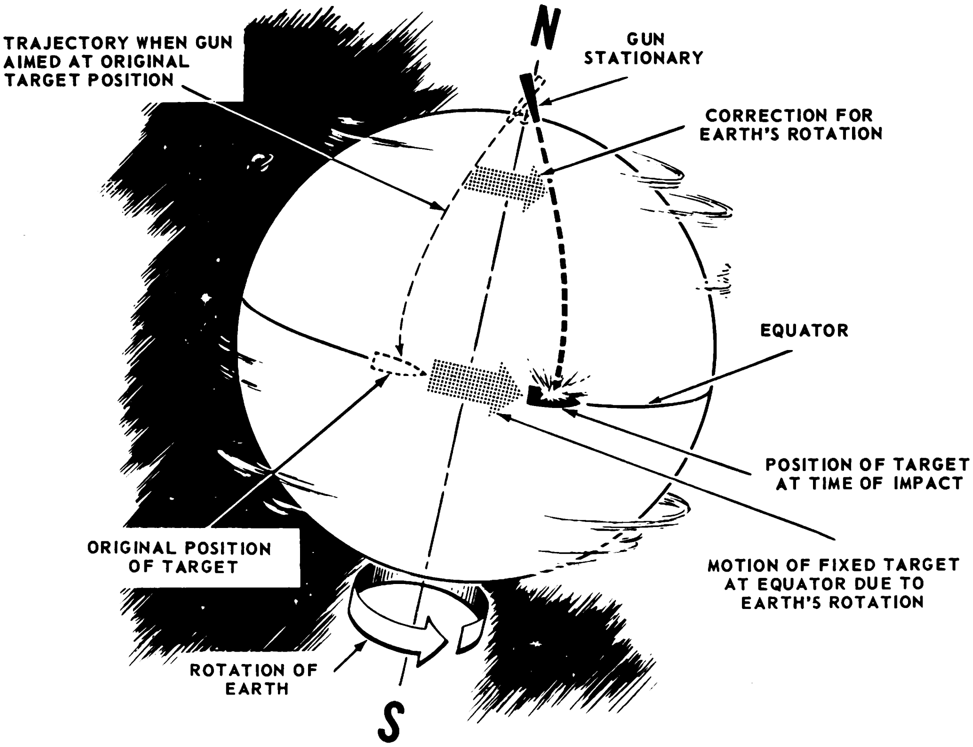

N
S
TRAJECTORY WHEN GUN AIMED AT ORIGINAL TARGET POSITION
GUN STATIONARY
CORRECTION FOR EARTH'S ROTATION
EQUATOR
POSITION OF TARGET AT TIME OF IMPACT
MOTION OF FIXED TARGET AT EQUATOR DUE TO EARTH'S ROTATION
ORIGINAL POSITION OF TARGET
ROTATION OF EARTH
12.10

Figure 2-10.—Effect of earth's rotation.

projectile fired from a stationary gun. It is time now to correlate the facts into a usable form. This has been done for us in the range tables. Every possible combination of naval gun, projectile, and initial velocity has its range table. A sample portion of a range table for a 5"/38 gun firing AA common projectiles with an initial velocity of 2600 ft/sec is shown in figure 2-11.

As you can see, a great deal of information is included in a range table. These tables are available as Ordnance Pamphlets (OPs). Your ship will have range tables for each battery installed and for all possible firing circumstances.

The first eight columns of the table describe the characteristics and the shape of a projectile's trajectory fired from a stationary gun. The figures in the columns have been determined by experimental firings of this particular combination and by higher mathematics at the Naval Weapons Laboratory.

During an experimental firing, it is assumed that the following conditions exist:

1. The earth is flat, and does not move.
2. The atmosphere is standard.
3. No wind is blowing.
4. The elevation angle is measured from a horizontal plane—the earth's surface.
5. The gun and target are both stationary.
6. The projectile is standard.
7. The initial velocity has the designed value.

Experimental firings are conducted under conditions as close as possible to those listed above. The actual trajectories are carefully measured. Obviously, some of the assumed conditions are impossible to obtain. Deviations from these conditions are taken into account in the computations on which the range tables are based.

USING THE RANGE TABLE

Notice that column 1 of the range table tabulates a series of ranges in 100-yard steps. The page illustrated runs from 7000 yards to 9000 yards. The entire range table for this gun runs from 1000 yards to 18,200 yards.

Column 2 gives the angle of departure of the gun barrel for each range in degrees and

Initial Velocity=2600 F. S. Weight of Projectile=54 Pounds. Length of Projectile=4.15 Calibers. Radius of Ogive=5.25 Calibers.

Range	Angle of elevation		Increase in angle of elevation for 100 yards increase in range	Angle of fall	Time of flight	Striking velocity	Drift	Danger space for a target 20 feet high	Maximum ordinate	Change of range for variation of +10 feet per second initial velocity	Change of range for variation of -1 pound in weight of projectile	Change of range for variation in density of air of -10 per cent	Change of range for wind component in plane of fire of 10 knots	Change of range for motion of gun in plane of fire of 10 knots	Change of range for motion of target in plane of fire of 10 knots	Deviation for lateral wind component of 10 knots	Deviation for lateral motion of gun perpendicular to line of fire, speed of 10 knots	Deviation for lateral motion of target perpendicular to line of fire, speed of 10 knots	Change in height of impact for variation of 100 yards in sight bar
1	2	2a	2b	3	4	5	6	7	8	10	11	12	13	14 •	15	16	17	18	19
Yards	° ′	Minutes	Min.	° ′	Seconds	F.S.	Yards	Yards	Feet	Yards	Yards	Yards	Yards	Yards	Yards	Yards	Yards	Yards	Feet
7000	5 00.1	300.1	7.4	8 14	12.06	1232	22.8	46	590	37	5	275	31	37	68	22	46	68	43
7100	5 07.5	307.5	7.5	8 30	12.31	1220	23.8	45	615	37	5	282	32	37	69	23	46	69	44
7200	5 15.0	315.0	7.6	8 46	12.57	1208	24.8	43	640	38	4	289	33	37	71	24	47	71	46
7300	5 22.6	322.6	7.8	9 02	12.83	1197	25.8	42	670	38	3	296	34	38	72	24	48	72	47
7400	5 30.4	330.4	8.0	9 19	13.09	1186	26.9	41	700	38	2	303	35	38	74	25	49	74	49
7500	5 38.4	338.4	8.1	9 36	13.36	1175	28.0	40	730	39	1	310	36	38	75	26	49	75	50
7600	5 46.5	346.5	8.2	9 53	13.63	1165	29.1	39	760	39	0	317	38	38	77	27	50	77	52
7700	5 54.7	354.7	8.4	10 11	13.90	1155	30.3	37	790	39	– 1	324	39	38	78	27	51	78	54
7800	6 03.1	363.1	8.5	10 29	14.17	1146	31.5	36	820	40	– 2	331	40	39	80	28	52	80	55
7900	6 11.6	371.6	8.6	10 47	14.45	1137	32.7	35	855	40	– 3	338	42	39	81	29	52	81	57
8000	6 20.2	380.2	8.8	11 06	14.73	1128	34.0	34	890	40	– 4	345	43	39	83	30	53	83	59
8100	6 29.0	389.0	9.0	11 25	15.01	1119	35.3	33	925	40	– 5	352	44	39	85	31	54	85	61
8200	6 38.0	398.0	9.2	11 44	15.29	1111	36.6	32	960	40	– 6	359	46	39	86	32	54	86	63
8300	6 47.2	407.2	9.3	12 04	15.58	1103	38.0	31	1000	41	– 7	366	47	39	88	33	55	88	64
8400	6 56.5	416.5	9.5	12 24	15.87	1095	39.4	30	1040	41	– 8	373	48	40	89	34	55	89	66
8500	7 06.0	426.0	9.6	12 44	16.16	1088	40.8	30	1080	41	– 8	380	50	40	91	35	56	91	68
8600	7 15.6	435.6	9.8	13 05	16.45	1081	42.3	29	1120	41	– 9	386	51	40	92	36	56	92	70
8700	7 25.4	445.4	10.0	13 26	16.75	1074	43.8	28	1160	42	–10	393	53	40	94	37	57	94	72
8800	7 35.4	455.4	10.1	13 47	17.05	1067	45.4	27	1205	42	–11	400	55	40	96	38	58	96	74
8900	7 45.5	465.5	10.3	14 09	17.35	1060	47.0	26	1250	42	–12	406	56	10	97	39	58	97	76
9000	7 55.8	475.8	10.4	14 31	17.65	1054	48.6	26	1295	42	–13	413	58	40	99	40	59	99	78

12.5.0

Figure 2-11.—Surface range table for 5" gun.

minutes, while column 2 a gives the same angle in minutes, i.e., 2° equals 120 minutes, etc. Column 2a is included because the sight angle scales of modern guns are usually calibrated in minutes rather than degrees.

Suppose you want to hit a target 8100 yards away. In column 1 you will find 8100 yards. Opposite 8100 yards in column 2 you will find that an angle of departure of 6°29'.0 is needed to get this range. This angle of departure is set on the gun.

From column 6 of the table you see that at this range drift is equal to 35.3 yards. As you know, this must be converted to angular mils. Since a 35-yard deflection at 1000 yards would be equivalent to 35 mils, the mils required to produce a 35-yard deflection at 8100 yards must be 35/8.1 or 4.3 mils.

Because drift is always to the right, the line of fire is offset to the left by 4.3 mils; then you are ready to fire. If all the assumed conditions are present the trajectory will be exactly as described in the first eight columns of the table, and you will hit the target.

Your chances of firing under standard conditions are for all practical purposes nonexistent. The remaining columns show how deviation from standard conditions affect the trajectory described in the first eight columns. We will use the range table to compute the corrections for these deviations. We will, however, continue to consider the gun and target stationary, with no wind blowing. Before we consider these factors, it would be best to have a look at the tracking or relative motion problem.

Algebraic signs are given to the values in the columns to indicate the direction of the error caused by the deviation at the head of the column. If there is no sign, a positive sign is assumed. Positive signs indicate that the factor will cause (1) range to increase, (2) elevation to increase, or (3) deflection to the right, and (4) the deviation is higher than the standard. Negative signs indicate that the factor will cause (1) range to decrease, (2) elevation to decrease, or (3) deflection to the left and, (4) deviation is below the standard.

The correction necessary to compensate for an error is equal and opposite to the error.

Effect of Air Density

Any variation of air density from the standard will have to be corrected. The chances are that the air density, when you fire, has some different value than standard. A value of air density is obtained by the ship's aerologist and furnished to the weapons department in the form of PERCENTAGE VARIATION from the standard density. The air density varies with different altitudes, and the effect of the density depends on whether you are firing at long or short range. At long range most of the trajectory is in the thin upper air. This requires the use of an average value, called BALLISTIC DENSITY, for that range.

Now look at column 12 of the range table. It shows the error which will be produced if the average air density is 10 percent less than standard density. If the density is less, the resistance to the movement of the projectile will be less, and the projectile will go farther. In column 12, opposite 8100 yards in the range column, you will find a value of 352 which means that, if you set the angle of departure of 6°29' into the gun and air density is 10 percent below standard, you will overshoot the target by 352 yards.

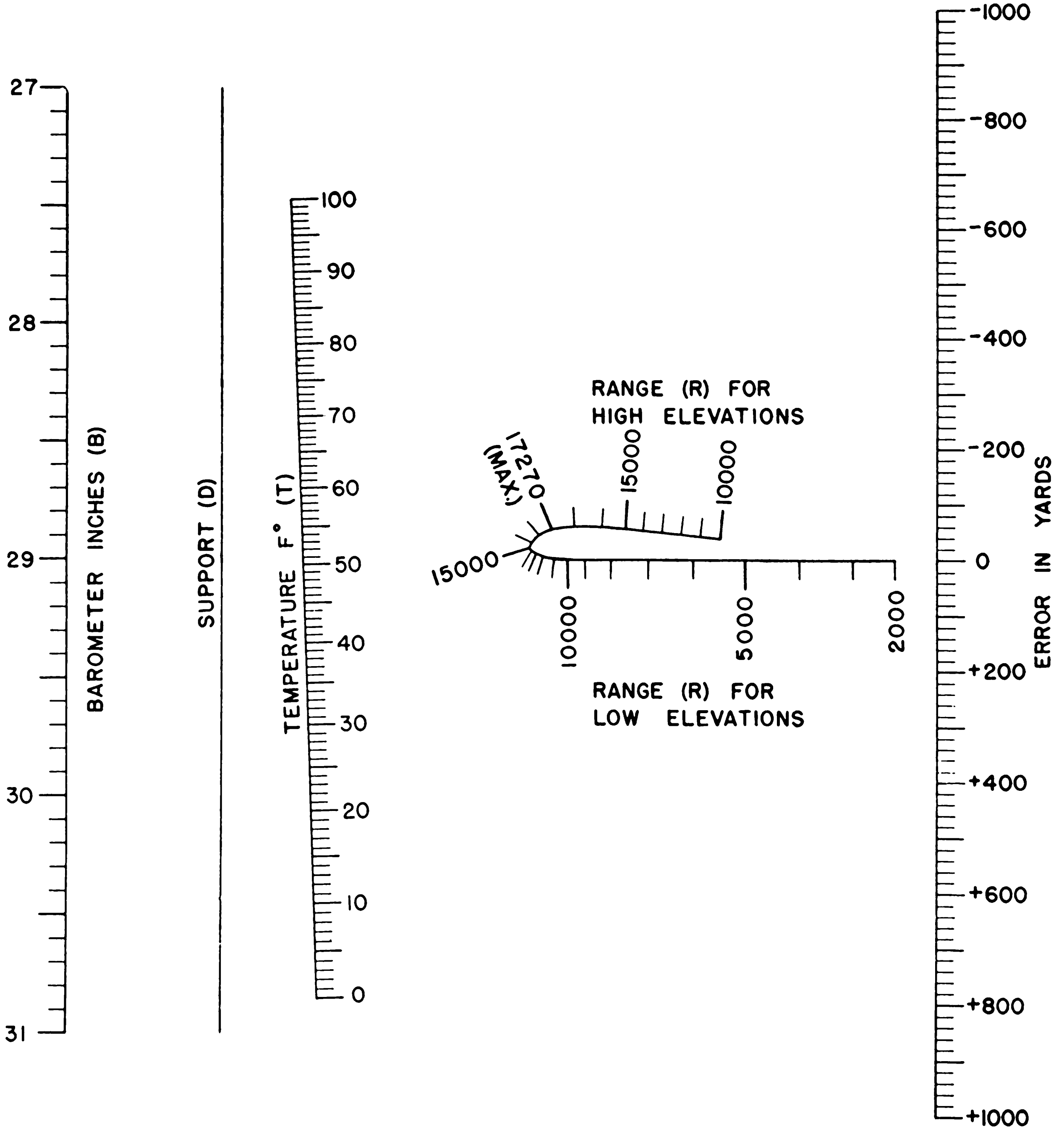
Now suppose the density were only 8 percent low. Then the error will be 8/10 of 352 yards or an error of 280 yards. Since you will be shooting over, you will have to subtract this 280 yard error from your original range of 8100 yards, which leaves you 7820 yards. Referring to column 2 of your range table for 7820 yards, you find your new angle of departure to be 6°03. 1.

In case there is no aerologist aboard to give you a value of ballistic density, you can work out an approximate air density correction by means of a graphic device called a nomogram. An air density nomogram is included in most range tables, and one is shown in figure 2-12.

Using The Air Density Nomogram

To use the nomogram, lay a ruler between the point on the temperature line corresponding to present air temperature and the appropriate point on the barometer reading line, and make a mark at the point where the ruler crosses the vertical line labeled SUPPORT D. Now lay the ruler between this point and a point on the line marked range (R) for HIGH elevations or range (R) for LOW elevations. Mark the spot where the ruler crosses the vertical line marked ERROR IN YARDS.

The spot where the ruler crosses the vertical line marked ERROR IN YARDS is the error in



12.6

Figure 2-12.—Air density nomogram.

range due to a nonstandard air density. Make a correction to range-table range to compensate for this error and get a revised value of angle of departure.

The use of the nomogram is more accurate than results obtained from using column 12 with surface observations, as the nomogram takes into account the ratio between mean measured and standard density for the actual maximum ordinate obtained.

Changes in Initial Velocity

The range table is based on a U, (initial velocity formerly symbolized as I.V.), of 2600 ft/sec. This is the initial velocity that the gun is designed to have, but few guns in the fleet actually develop their designed velocities. There are two reasons for the lower initial velocities obtained in actual firing.

One reason is the wear of the gun barrel. Every time the gun is fired the inside of the barrel is slightly worn away, so that the bore becomes enlarged. This reduces the pressure behind the projectile and lowers the initial velocity.

Records are kept of the number of times a gun is fired. In this record a round of target ammunition using a reduced powder charge is counted as an equivalent fraction of a service round. The total of service rounds plus target rounds counted in this way is called EQUIVALENT SERVICE ROUNDS. Curves have been worked out experimentally for each type of naval gun, showing the U loss to be expected after any number of equivalent service rounds fired.

The same thing may be accomplished by measuring the enlargement of the bore with a STAR GAGE AND EROSION GAGE. Curves are available showing the U loss for any amount of enlargement. For example, if the bore of a 5''/38 gun Mk 12 is enlarged 0.04 inches, the U will be reduced about 28 ft/sec. This is more accurate than counting the rounds fired. The usual procedure is to star-gage guns periodically to get a value of U loss, and then keep track of rounds fired between star gagings.

The second reason for lower initial velocity is the change in the condition of the powder. With modern manufacturing method the chemical composition of smokeless powder does not vary to any great extent, but powder has a different amount of strength at different temperatures. The warmer the power, the more powerful it is.

Naval guns are designed to obtain standard U when the powder has a temperature of 90°F, and every degree of variation from this standard temperature will change the 5''/38 U by approximately 2 ft/sec. For instance, if the powder being used has a temperature of 80° F, you know at once that the U will be 20 ft/sec less than the rated value. Since magazine temperatures are normally below standard this factor will usually reduce U. And since powder temperature changes slowly, the average magazine temperature for the past several days should be used.

Combining these factors, erosion and powder temperature, you will get a figure for the total change in U from the standard conditions.

Column 10 of the range table gives you the change in range for an increase of 10 ft/sec in U. Suppose the figures on gun erosion and powder temperature indicate an U loss of 38 ft/sec. The range is still 8100 yards. You will find in column 10, opposite this range, a value of 40 yards. To find the effect on the range with a 38 ft/sec U loss, multiply 40 times 38/10, obtaining 152 yards. This means that if you use the angle of departure given by the range table for 8100 yard range, you will under shoot by 152 yards. Obviously, if you are falling short, the thing to do is to increase range.

Projectile Weight

Another assumption that was made in computing the range table was that the weight and shape of the projectile were standard. However, in case it should be necessary to fire a projectile of nonstandard weight, column 11 of the range table gives the change in range to be expected if the projectile is reduced in weight by one pound.

Finding Gun Range

So far you have considered each of the errors in range separately, but in practice, all errors will be combined. Thus, in the previous examples, the variation in air density was causing an error of 280 yards over, while variation in U was causing an error of 152 yards short. The combined effect is an error of 128 yards over, or about 100 yards over. An over error requires a down correction, so you find the angle of departure corresponding to a range of 8100 minus 100 = 8000 yards.

The way the correction is applied is important as the correction will be equal in amount but opposite in sign to the error. In other words, a SHORT ERROR requires an ADD CORRECTION, while a LONG ERROR requires a DROP CORRECTION. The total correction is called the GUN BALLISTIC IN RANGE.

BALLISTIC IN THE FIRE CONTROL SYSTEM

Using a range table to solve the ballistic problem is time consuming. And we have little time when the shooting starts. From our study of ballistics we know that to hit a target these problems must be solved. Normally it is the job of the fire control computer to solve the ballistic problem. The projectile's initial velocity, however, is calculated before the shoot, and is an input to the computer.

The range tables are built into the computer. For example, in a mechanical computer ballistic cams are used to solve the problem (fig. 2-13). These cams are cut so that if the input shaft is rotated by an amount proportional to the range, the cam follower will move an amount proportional to one of the columns of the range table—angle of departure, time of flight, etc.

The postfiring evaluation of a practice shot depends on the range tables. In the evaluation, the range table information is used as the criterion to judge the accuracy of the shot. The location of the projectile's impact point, as observed by spotters, and the point at which the fire control system computed it should have landed, are compared with the solution calculated from range table data. In this way we can judge the performance of a gun battery against proven standards.

ELEMENTS OF THE FIRE CONTROL PROBLEM

Before we discuss the surface fire control problem, you should understand two fundamental angles that help to determine gun position. These angles are SIGHT ANGLE and SIGHT DEFLECTION. They will be explained with respect to a gun sight telescope. This approach will give us the opportunity to introduce and explain some of the lines, angles, and planes that are basic to the fire control problem.

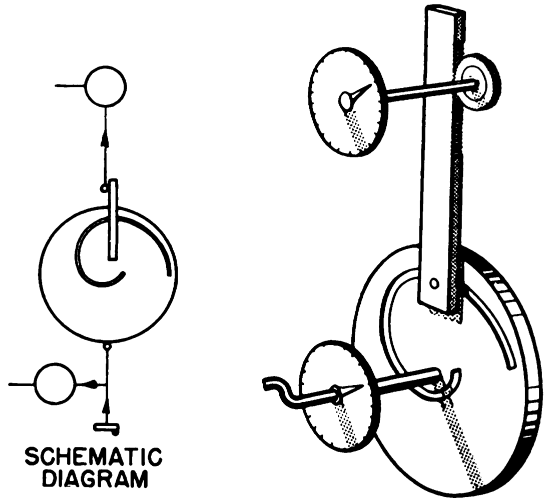


Figure 2-13.—A simple ballistic cam. 12.260

Let's consider the exterior ballistics in a surface gun battery. From our discussion of this subject, two important facts are apparent. First, the projectile takes a definite period of time—called the time of flight—to travel to the target. This element is present in all fire control problems. The second ballistic fact is that the projectile's trajectory is curved. The curvature is due to gravity and air resistance, which are always present. Consequently, the second factor is present to some degree in all fire control problems.

Although the ballistic portion of the fire control problem concerns many quantities, the time of flight and the trajectory's curvature are the ultimate facts we must consider if we are to hit the target. From this we can conclude that two basic lines are necessary. One, called the line of sight (LOS), is to establish the position of the target with respect to the gun; the second, called the line of fire (LOF), is to establish the position of the gun bore with respect to the first line.

Until now we have not located the target with respect to the gun. We assumed the gun was on the target to begin with, and simply offset the gun bore for the ballistic corrections. To proceed further in this discussion we must establish the position of the target in the coordinates in which the gun bore is positioned. A gunsight telescope mounted parallel to the gun bore and moving with it should fill the bill. Or will it? Remember that the LOF must be offset from the LOS. To establish the LOS, using a telescope on the gun, the axis of the gun bore must be parallel to the telescope axis. But to offset the LOF from the LOS, there must be some independent motions between the two axes.

In the explanation of the offset of the LOF from the LOS there are several definitions that should be stated beforehand.

Horizontal Plane

The line marked Line of Sight (fig. 2-14) is in the horizontal plane. The horizontal plane (sometimes called the horizontal) is an imaginary plane tangent to the earth's surface at

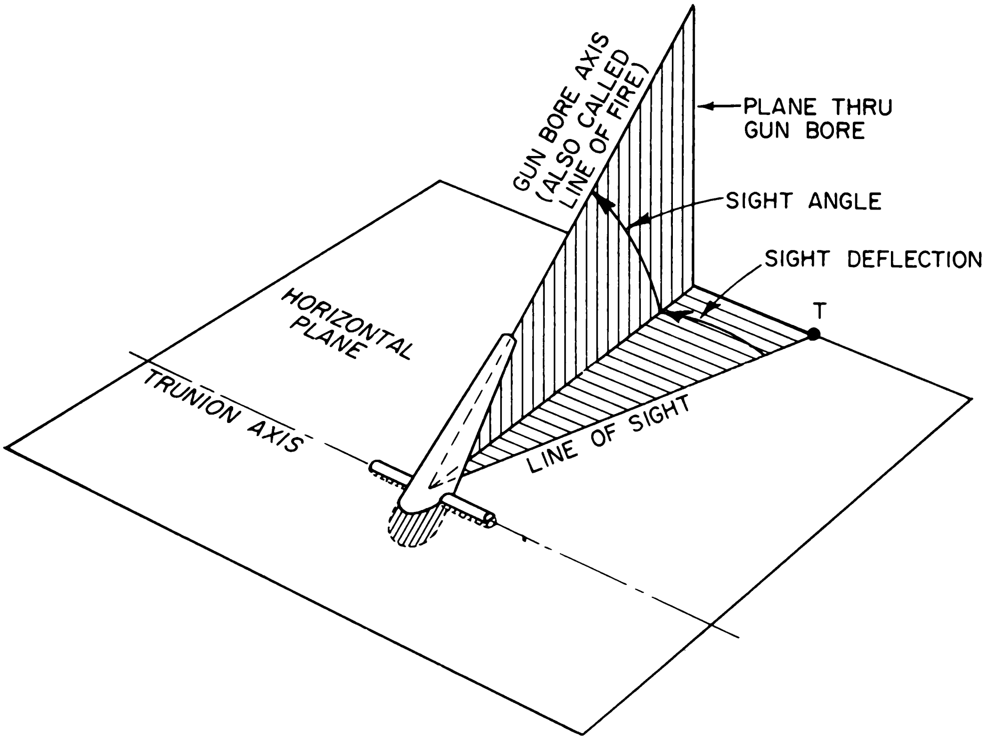


Figure 2-14.—Sight angle and sight deflection in the surface problem.

the gun. Solution of the surface fire control problem is based on the assumption that the gun and target are in the same horizontal plane. The earth's surface is assumed to be flat.

The LOS is a straight line connecting the gun sight with the target. To place the LOS on the target the gun has two axes about which it is free to move. The gun can move in train in the plane containing the axis of the gun trunnions. It can move in elevation about the trunnions, in a plane perpendicular to that in which the gun trains.

Line of Fire

Figure 2-14 contains another line that needs defining. This is the line along which the gun must be pointed in order to hit the target. A more formal definition would be that it is the projection of the axis of the bore of the gun on the horizontal plane through the trunnions. The LOF, as you can see in figure 2-14, is established by two lead angles. One is sight angle and the other is sight deflection.

Sight Angle

In our definition the deck is assumed to be horizontal, and reference is made to sight angle as it is set into a gun sight. Sight angle is the angle between the gun bore axis (LOF) and the line of sight. The angle is measured in a plane perpendicular to the trunnion axis. The plane passes through the gun bore. If the gun and target are in the horizontal plane, sight angle will be set in above the horizontal plane. Because in this case the line of sight lies in the horizontal plane, you can also say that sight angle will be set in above the horizontal.

Sight Deflection

In figure 2-14 notice that the line of sight, although lying in the horizontal plane through the trunnion axis, is NOT in the plane passing through the line of fire and perpendicular to the gun trunnions. Sight deflection is the angle by which the plane through the gun bore is deflected from the line of sight. The angle is measured in the horizontal plane through the trunnion axis which contains the line of sight.

SETTING SIGHT ANGLE AND SIGHT DEFLECTION

Here, we will discuss the principles of setting sight angle and sight deflection into the gunsights. Also, this discussion deals with the provision at the gun whereby sight angle and deflection are converted to the angle of gun position relative to the line of sight. This is illustrated in figures 2-15 and 2-16.

Because of the effect of gravity, and other factors, if the gun barrel is aimed directly at a stationary target, the projectile will fall short and to one side of the target. Sight angle and sight deflection compensate for these factors. These angles are introduced at the gun, where they offset a special gunsight installed at the gun.

In considering first how gun elevation above the line of sight is obtained, let us start with the sight angle and sight deflection at zero. Under these conditions the line of sight and the bore of the gun are parallel. Now, when the gun pointer turns his handwheels to place the line of sight on a target, the gun bore will also point to the target. Now let us assume we have determined that for a target range (R), (fig. 2-15), the gun must be elevated 30° above the line of sight in order to hit the target. This elevation is accomplished in two steps. Although these steps are described separately, they are performed simultaneously.

STEP 1.—Assume that, as shown in figure 2-15 the fire control computer has computed a sight angle of 30° and transmitted it to the gun. The sightsetter, who is stationed at the gun sight-setting mechanism, sets the necessary sight angle Vs into the sight. This DEPRESSES the gun sight 30° below the gun bore. The sight-setting mechanism is always designed so that the line of sight can be depressed independently of the gun. However, the gun elevating mechanism is so designed that any movement of the gun by the pointer will carry the gunsight with it.

STEP 2.—Since the sightsetter has depressed the line of sight, the gun pointer now sees his cross wire below the target. He then elevates the gun with his handwheels, carrying the gun sight with it. The pointer continues to elevate the gun and sight until his line of sight is again on the target, at which time the gun barrel will be elevated 30° above the line of sight; the amount

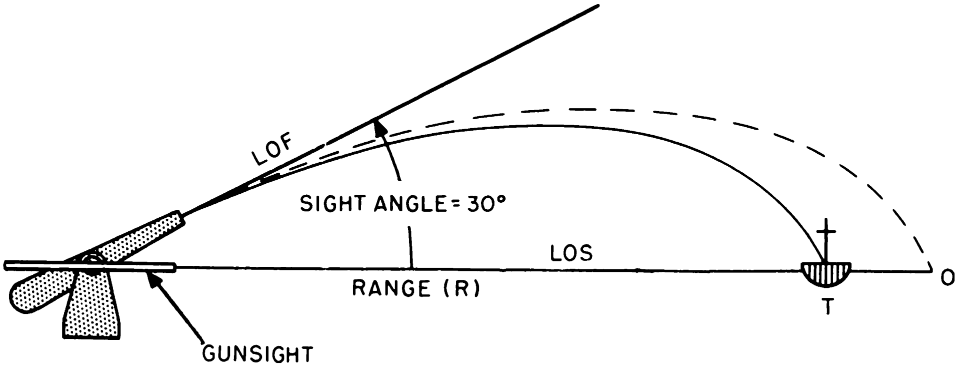


Figure 2-15.—Sight angle.

12.12

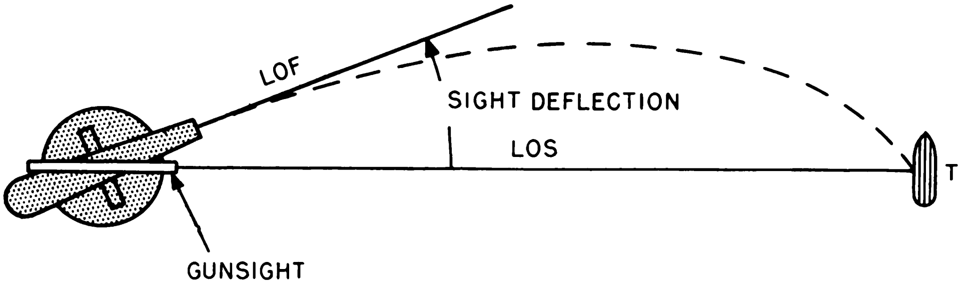


Figure 2-16.—Sight deflection.

12.13

that the sight was originally depressed. This final result is illustrated by the solid lines in figure 2-15. Thus the mechanical arrangement at the gun is such that so long as the pointer keeps on the target, the gun will be elevated above his line of sight by sight angle Vs.

Now assume that with this elevation of 30° above the line of sight, the projectile overshoots the target as represented by the dashed line, and falls into the water at point 0. The 30° angle of gun elevation was evidently too large, and to correct this range error, the angle between the gun bore and the line of sight must be decreased. This correction may also be described in two steps. First, the sightsetter elevates the sight (determining the amount of elevation from a scale at the sight) the proper amount to correct the error in range. By doing so, he decreases the original value of sight angle. The pointer's wire will now be ABOVE the target, and the gun pointer will have to DEPRESS the gun until his line of sight is again on the target. Gun elevation above the line of sight will now be less than before, and a hit should result.

The problem of introducing sight deflection is similar to that of introducing sight angle, the difference being that now we are concerned with deflecting the gun bore in the horizontal plane, by training the gun. See figure 2-16.

Again assume that the gun axis and line of sight are parallel. Assume that ballistic factors would cause the projectile to fall to the right of the target if the gun bore were aimed at the target. For this reason, the gun bore itself must be deflected to the left of the line of sight established by the trainer's sight.

The deflection correction, sight deflection, is introduced into the gunsight by the sightsetter (through a deflection scale) to offset the sights to the right. With this, the trainer sees his line of sight to the right of the target and he trains the gun left in order to get it back on the target. The trainer thereby introduces the correct left sight deflection into the gun itself, so that the tendency of the projectile to fall to the right of the line of fire is corrected.

Before learning about the complications to the fire control problem introduced when both target and own ship are moving, let's review the basic or common factors found in any form of the fire control problem.

We have seen how the line of sight establishes the position of the target in relation to the gun. Sight angle and sight deflection are measured from the line of sight to the line of fire. Both of these lines intersect a point at the gun trunnion. We can call this the reference point, or origin. The angle formed by the two lines intersecting at the origin is the lead angle or prediction angle needed to score a hit on the target. In conclusion, the LOF, LOS, and prediction angle are three common factors found in any form of the fire control problem.

The prediction angle is made up of two types of predictions: ballistic predictions which you have just studied, and relative motion prediction which is the next topic for discussion.

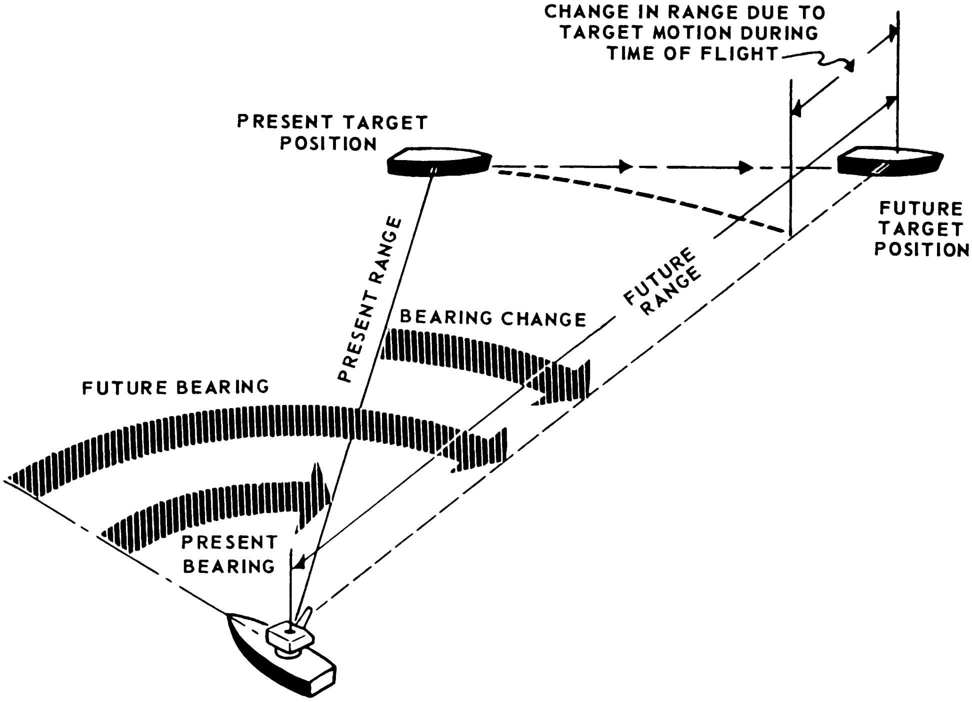
Now you are ready to go on and apply the things you have already learned to the study of the problem of hitting a moving target from a moving ship. All of the principles of interior and exterior ballistics that apply to a stationary target and gun also hold true when both own ship and target are moving.

THE PROBLEM OF HITTING A MOVING TARGET FROM A MOVING SHIP

When an enemy ship is sighted and comes within range, it is the job of fire control to solve the fire control problem so that your ship's guns can hit the target. If the enemy were obliging enough to remain in one place and your ship were also brought to a stop, the required elevation and traverse gun settings could be determined by considering only the factors of interior and exterior ballistics for a fixed gun and target, as discussed on the preceding pages. No enemy ship would be foolish enough to remain still under fire, however, and your own ship doesn't want to be a "sitting duck" for the enemy's fire either. So both the target and your own ship will keep moving during battle. As a result the target range and bearing are continually changing, necessitating constant changes to gun elevation angle (sight angle) and sight deflection. Figure 2-17 shows how target motion affects the target range and bearing.

In order to make the proper corrections, it is necessary to know in what direction and at what speed the target ship is moving. With this information it is possible to predict the position the target will occupy after the time of flight of the projectile has elapsed. The gun is then directed so that the projectile will strike the "future position" of the target.

Another factor in the fire control problem is that the velocity of the ship will be imparted to the projectile and will affect its trajectory. To illustrate this effect, consider the target as



12.14

Figure 2-17.—How target motion affects range and bearing.

standing still and the firing ship in motion. See figure 2-18. As the gun is fired the projectile has two velocities—its own U and that due to ship's motion. If the ship's velocity is not considered, the projectile will land short, beyond or to one side of the target, depending on the direction of ship's motion. Thus the effect of ship's speed and direction on projectile trajectory must be considered to obtain accurate fire.

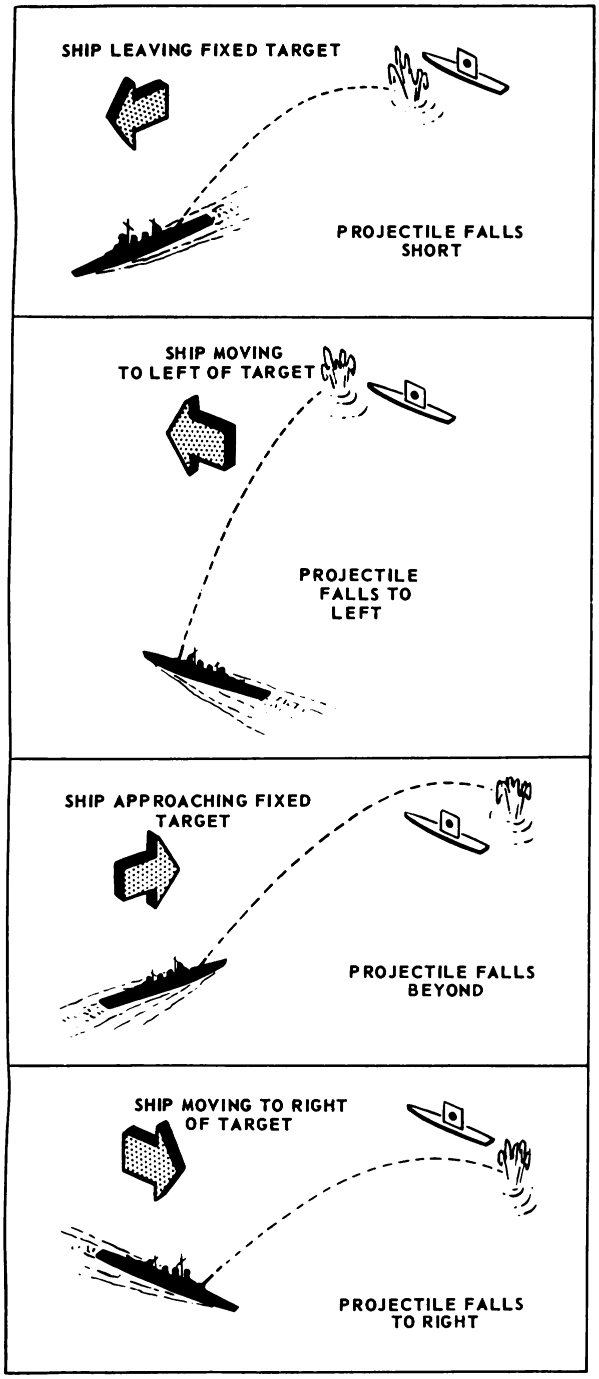
Relative Motion

As we have shown, the relative motion between own ship and target must be considered. Moreover, the amount of relative motion which will occur during the projectile's time of flight must be predicted and a future position of the target determined. Since the target will not voluntarily give its course and speed we must obtain this information by another method.

The target's course and speed in addition to a measure of the amount of relative motion are obtained by tracking the target. Tracking is the process of continuously measuring target position with respect to own ship. A timed rate of change of target position will give the rate of relative motion. Since own ship's course and speed, hence own ship's motion, are known, any additional motion is due to target motion. Target course and speed can be determined from this information.

Tracking is accomplished by a fire control director working in conjunction with a computer or rangekeeper. The director establishes a surface target's present position by the quantities of range and bearing (fig. 2-17). Target position is measured by either optical devices (telescopes and rangefinder), or by radar. Bearing is measured in the deck plane, clockwise from the bow of the ship to the plane perpendicular to the deck through the LOS. Range to the target is measured in the plane of the LOS. The director keeps the LOS or tracking line on the target, and furnishes the computer with continuous range and bearing measurements.

A timed rate of change of range and bearing are determined by the computer. These are the relative rates we need to compute the future position of the target. This is done by multiplying the rates by time of flight. The predicted changes in range and bearing are added to the target's position at the instant of fire to determine its future position. The ballistic corrections are added to the target's future range and bearing to obtain LOF.


SHIP LEAVING FIXED TARGET
PROJECTILE FALLS SHORT
SHIP MOVING TO LEFT OF TARGET
PROJECTILE FALLS TO LEFT
SHIP APPROACHING FIXED TARGET
PROJECTILE FALLS BEYOND
SHIP MOVING TO RIGHT OF TARGET
PROJECTILE FALLS TO RIGHT

12.15

Figure 2-18.—How own ship's motion affects range and deflection.

Now that we have established the LOF there is another correction to the flight of a projectile which we must consider. Standard conditions in the range table are based on the assumption that the air is still. But the earth's atmosphere is seldom without motion, and we must consider the effect of wind on the projectile's flight.

Wind Effect

If you have ever played football on a windy day, you are familiar with the effect of wind on an object in flight. Depending on the wind direction and velocity, your well-aimed "forward pass" may have curved to the right or left, or fallen short of or beyond the point where you wanted it to land.

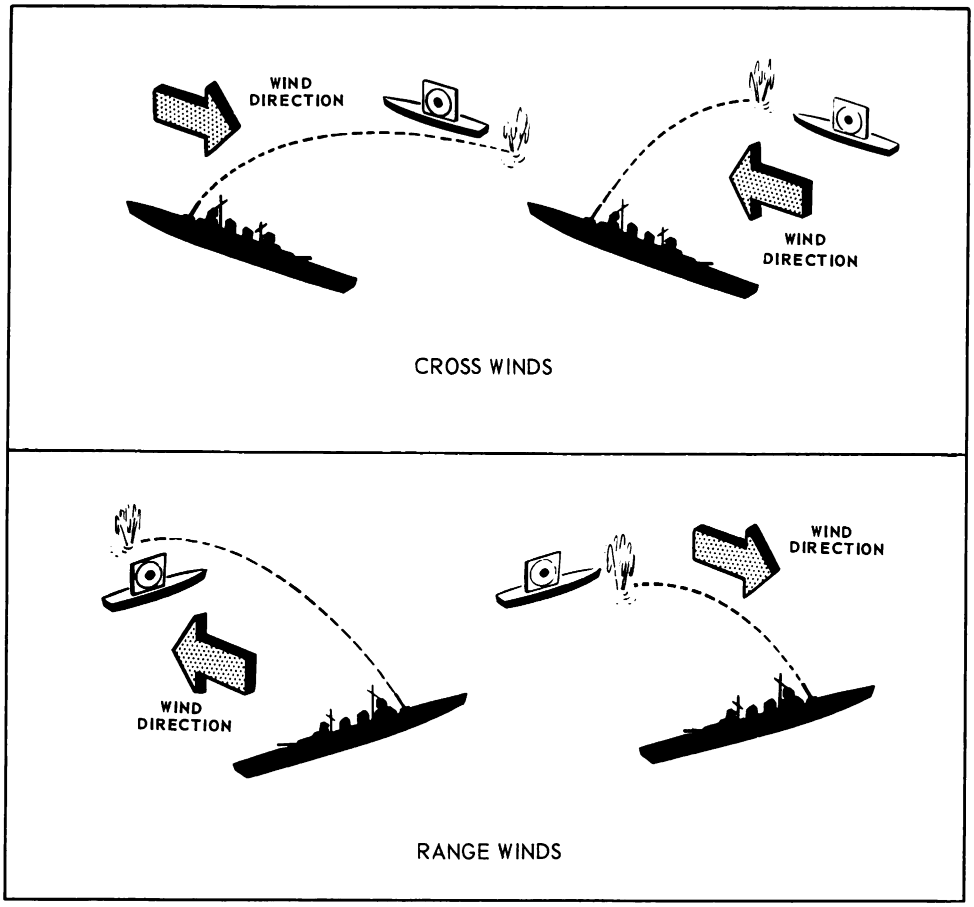
Wind has exactly the same effect on a projectile in flight. The effect of wind can be seen in figure 2-19. If the wind blows from the left the projectile's trajectory will turn to the right, and vice versa. If the projectile is headed into the wind its range will be decreased, and if it travels with the wind the range will be increased. You can see that effects of wind must be considered in the solution of the fire control problem.

We can define a wind that is blowing at right angles (sometimes written as 90 degrees or perpendicular) to the projectile's LOF as a "cross wind;" and if it is blowing along the LOF, either with or against the projectile, it is called a "range wind."

If the wind is blowing along the LOF against the projectile, the projectile will fall short of the target. To compensate for this we must elevate the gun to increase the range of the projectile. Under the same conditions, if the wind is blowing with the projectile, the projectile will land beyond the target. To compensate for this we must depress (lower) the gun to decrease the range.

If the wind is blowing from the right at 90° to the LOF, the projectile will land to the left of the target. To compensate for this we must train the gun to the right. If the wind is blowing from the left at 90° to the LOF, the projectile will land to the right of the target. To compensate for this we must train the gun to the left. The effects and corrections for both types of wind are shown in figure 2-20.

The examples given here are special cases. Obviously, wind does not always blow directly at right angles to the line of fire or directly with or against the projectile's LOF. If the



12.8

Figure 2-19.—Types of winds and their effects.

wind were cooperative enough to perform in this manner, it would be a relatively simple matter to compute the corrections required when the wind velocity is known. Usually, however, the wind blows at some other angle to the LOF. In order to correct for range and cross winds, it is necessary to resolve the true wind into components in line with and perpendicular to the LOF. When this is done, each component can be treated individually and the proper gunsetting adjustments made.

Obviously the longer a projectile remains in flight the more its course will be altered by the wind. Hence the effect of wind increases with range.

Two other factors which affect the amount the projectile deflects are wind speed and projectile size. Obviously, the greater the wind velocity, the greater the effect on the projectile. Also, as was true for deflection due to drift, large projectiles have more initial momentum (mass times velocity) and can resist the effects of wind better than small projectiles.

Corrections for the effects of wind are only approximate because wind speed and direction are usually different at various levels. For instance, the wind might be blowing from the north on the surface of the ocean, and from the south at an altitude of 6000 feet. In such a case the projectile's course will be affected differently as it is acted on by the wind at various levels of its flight.

Wind conditions at different elevations are determined by observations from an airplane or by observing the movements of a small balloon. If it is found that the projectile's trajectory will take it through winds which move in opposite directions, a "weighted ballistic wind" must be used to compute gunsetting corrections. This ballistic wind makes allowance for variations in wind velocity and direction at different levels, and for the length of time the projectile is in each level.

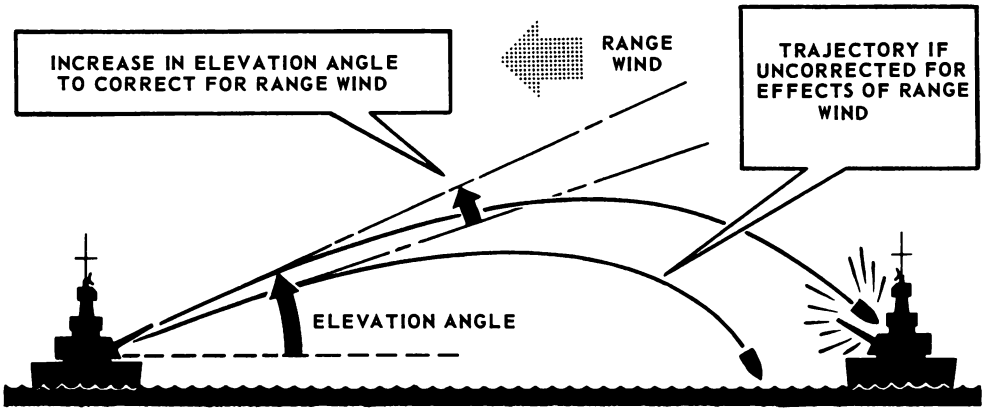
If the projectile's trajectory is low and passes through winds of one direction only, surface wind is used to compute corrections.

This is but a thumbnail sketch of the relative motion and prediction problems within the fire control problem. A detailed description and an actual solution are given in a later volume in this series of training courses.

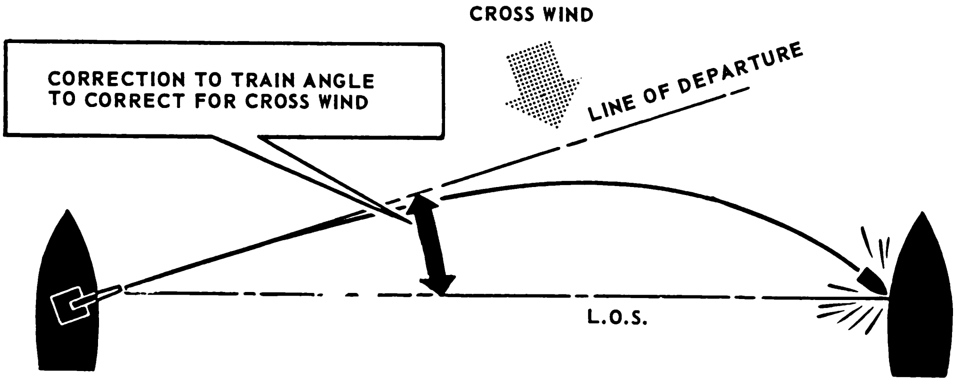
REPRESENTATIVE SURFACE GUN SYSTEM

As stated previously, the job of the fire control system is to solve the fire control problem. In this discussion we will loosely associate the problem with a system. This will be done by a brief functional description of the major units in a surface gun system. So far we have mentioned the director, the computer (rangekeeper), and the gun as separate units. Now we will tie them together into a simplified gun system as shown in figure 2-21.

THE DIRECTOR serves as the eyes of the system. It is located high in the superstructure. It establishes the present position of the target and transmits target data to the computer. The director tracks the target's movements by keeping its LOS on the target. Hence continuous target position information is furnished to the computer. Target data from the director may also include an estimate of target course and speed, identification as to the type and size of the target, and any other information concerning the target and firing situation which may be useful.


INCREASE IN ELEVATION ANGLE TO CORRECT FOR RANGE WIND
RANGE WIND
TRAJECTORY IF UNCORRECTED FOR EFFECTS OF RANGE WIND
ELEVATION ANGLE

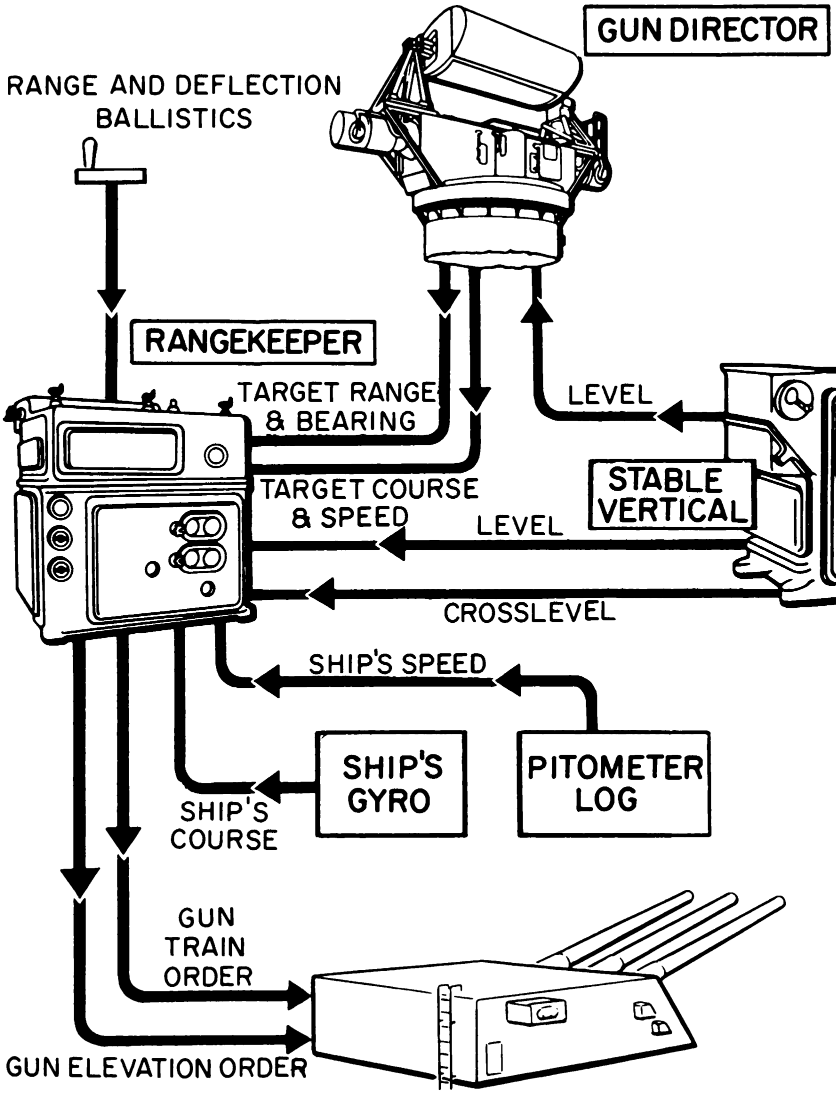
CORRECTING FOR THE EFFECTS OF RANGE WIND



CORRECTING FOR THE EFFECTS OF CROSS WIND

12.9

Figure 2-20.—Correcting for the effects of range wind and cross winds.



12.261

Figure 2-21.—Simplified surface gun system.

THE COMPUTER receives the target data from the director. The computer is normally located in a protected compartment called the Plotting Room (Plot), deep in the interior of the ship. In addition to the director's outputs the computer receives other inputs such as own ship's course and speed, wind data, and ballistic correction data.

The computer solves for the lead angles, sight angle, and sight deflection. To solve for these angles the actual problem is simulated in the computer. The lead angles are added to target's present position quantities to obtain train and elevation gun orders. Both the lead angles and the gun orders are transmitted to the gun.

THE GUN has power drives which continuously follow the gun orders from the computer in their automatic mode of operation. In automatic the gun barrel is always pointed at the point of aim established by the fire control system. The lead angles are manual inputs into the gun's sightsetting system to position the gun sights back into the LOS.

The gun can be fired locally or from a remote station such as plot or the director. To provide centrally controlled concentrated fire from an entire gun battery, a remote station normally controls the firing.

STABILIZATION

Until now we have assumed that the deck plane is parallel to the earth's surface. The deck of a ship is, of course, nearly always tilted with respect to the horizontal. Thus we have two sets of reference planes; first, the earth's reference planes upon which the basic problem is solved, and second, the director's and the gun's reference plane, (the ship's deck plane). Therefore, we must reconcile the two reference systems to obtain consistently accurate fire.

The tilt of the deck plane is the result of the roll and pitch of the ship. These motions are measured with respect to the ship's center line axis. Generally speaking, these motions affect the fire control problem only because the LOS and LOF are measured with respect to the deck plane. They do not alter the relative position nor the relative motion between own ship and target as measured with respect to the horizontal plane. Hence roll and pitch are not a part of the basic fire control problem, but are a factor in the methods used by the gun system to establish the LOS and the LOF.

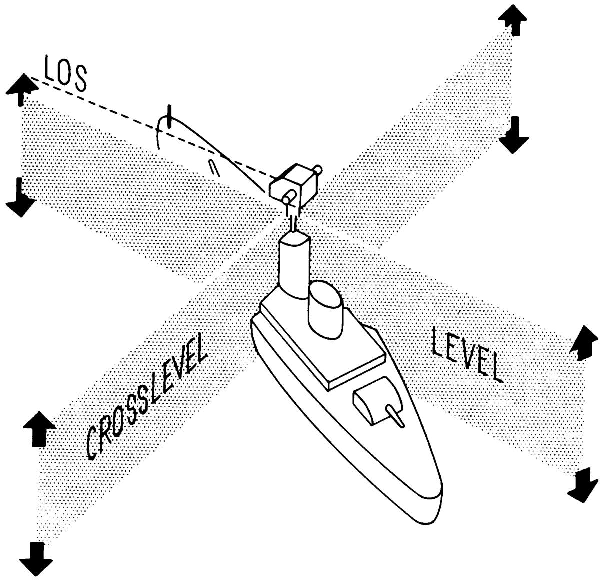
Level and Crosslevel

The tilt or inclination of the deck plane out of the horizontal plane is measured with respect to the LOS by the stable vertical (fig. 2-21). The method and devices used by the stable vertical, and by a similar instrument called the stable element, are explained in chapter 9 of this text. Here it is sufficient to know that the stable vertical measures the tilt of the deck in and across the LOS (fig. 2-22). Level and crosslevel are used to stabilize the LOS so that it will stay on target regardless of how the ship rolls and pitches.

Stabilizing the LOF

The effect of deck inclination on the LOF is solved by the computer. The corrections for deck inclination are included in the gun orders. Thus in automatic control the LOF is stablized by the gun orders.

The computer uses the level and crosslevel angles to solve the stabilization problem for the LOF. The computer can use these angles which are associated with the LOS because the ship is a solid structure. Therefore, all the units of the system will be tilted through an equal angle by an inclination of the deck out of the horizontal.



12.46

Figure 2-22.—Level and crosslevel.

First let's consider the inclination of the deck in the plane containing the LOF. To explain the correction for this inclination we must begin at the director. The director measures the elevation of the target with respect to the deck plane. Level is transmitted to the director to help keep the LOS on target by compensating for the movement of the deck plane out of the horizontal plane, (fig. 2-21). Director elevation goes into the makeup of gun elevation order in the computer. Hence, the inclination of the deck in the LOF is compensated for by the inclusion of director elevation in the gun elevation order.

Trunnion Tilt

Inclination of the deck across the line of sight tilts the gun trunnions out of the horizontal. For the purpose of simple explanation, the entire gun mount is considered to rotate around the line of sight. Figure 2-23 illustrates the effect of this motion. As you look along the LOS, you see that the gun trunnions are tilted to the right, swinging the elevated gun barrel to the right, and causing the line of fire to move to the right. This will cause a deflection error to the right, if it is not corrected. The same movement decreases the amount the gun bore is elevated above the horizontal, introducing a range error.

What actually has happened is that the sight angle and sight deflection, computed for the vertical and horizontal planes respectively, are now being applied in two entirely different planes; i.e., in planes perpendicular to and parallel to the deck plane, which is now inclined. To take the extreme case, a trunnion tilt of 90° would result in the bore axis being offset horizontally by the amount of sight angle and vertically by the amount of sight deflection.

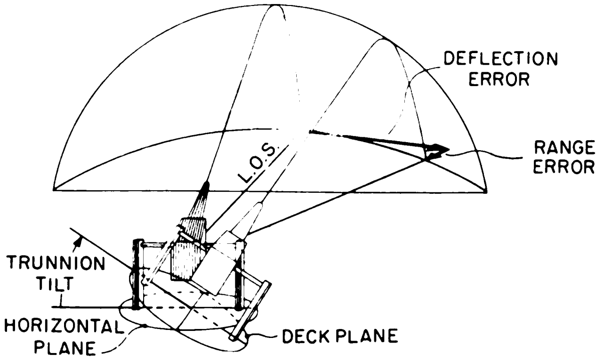
The deflection error resulting from trunnion tilt is normally large, and in the direction of the tilt. The range error is small, and always causes a decrease in gun range. An examination of figure 2-23 shows also that the angular displacment of the gun barrel depends upon the amount of gun elevation and the amount of trunnion tilt.

Problems Caused by the Location of Equipment

All weapons systems contain units that are located at different points on the ship. Look at figure 2-24A. This drawing shows the approximate position aboard ship of the units or major components that comprise a typical gun and missile weapon system. Notice that the radar set (director) and search radars are mounted as high as possible. This increases their range and provides an unrestricted view. But it causes a problem in vertical parallax.

Parallax

Figure 2-25 shows a typical gun and missile fire control system. The gun mount is forward; the radar set is amidships; and the launcher is aft. The figure shows that if the line of sight of the radar set is used as the reference from which the line of fire is measured, a convergence correction is needed at the gun and launcher if their destructive units are to hit the target. This correction is called horizontal (or train) parallax, as it is caused by the horizontal displacement of the equipments and gives rise to a train error. Horizontal parallax error increases as range decreases. You can see that the closer a target is to the ship, the greater the angle by which the gun and launcher must be toed-in to point at the target. The horizontal parallax error also depends on the relative bearing of the target. You can see that if you train all the elements on a target directly ahead or directly astern, the horizontal parallax error is zero.



12.45

Figure 2-23.—Effect of trunnion tilt on a gun.

Vertical parallax results from having different parts of the system at different heights. For example, assume a target for which the LOS from the radar has an elevation of 30 degrees. Obviously, the line of fire from the missile launcher will have to be elevated more than 30° above the horizontal if it is to intersect the LOS at the target. Vertical parallax error varies with target elevation; the error is zero for a target directly overhead.

Inclination of the Foundations Roller Paths

Each gun mount, launcher, radar set, and other major element in the weapon system, as it moves in train, rides on rollers running in a circular steel track called the roller path. In theory, all the roller paths should be in exactly parallel planes. In practice, they are not. Figure 2-24B shows exaggerated roller path inclinations of the elements in a typical gun and missile fire control system. Ideally, the roller path of each element should be parallel to that of the director or radar set used as a reference. In our basic system the roller path of the radar set has been carefully machined, and carefully mounted parallel to the deck. Thus, when the deck is parallel to the horizontal plane (no roll or pitch) the roller path of the radar set is also horizontal. Therefore the roller path of the radar is used as a reference from which to measure the inclination of the other elements of the system. The tilt of the launcher and mount shown in figure 2-24B are much exaggerated; in an actual weapons system these tilts are very small. But any tilt from the reference will cause an error in elevation, and this error must be corrected for.

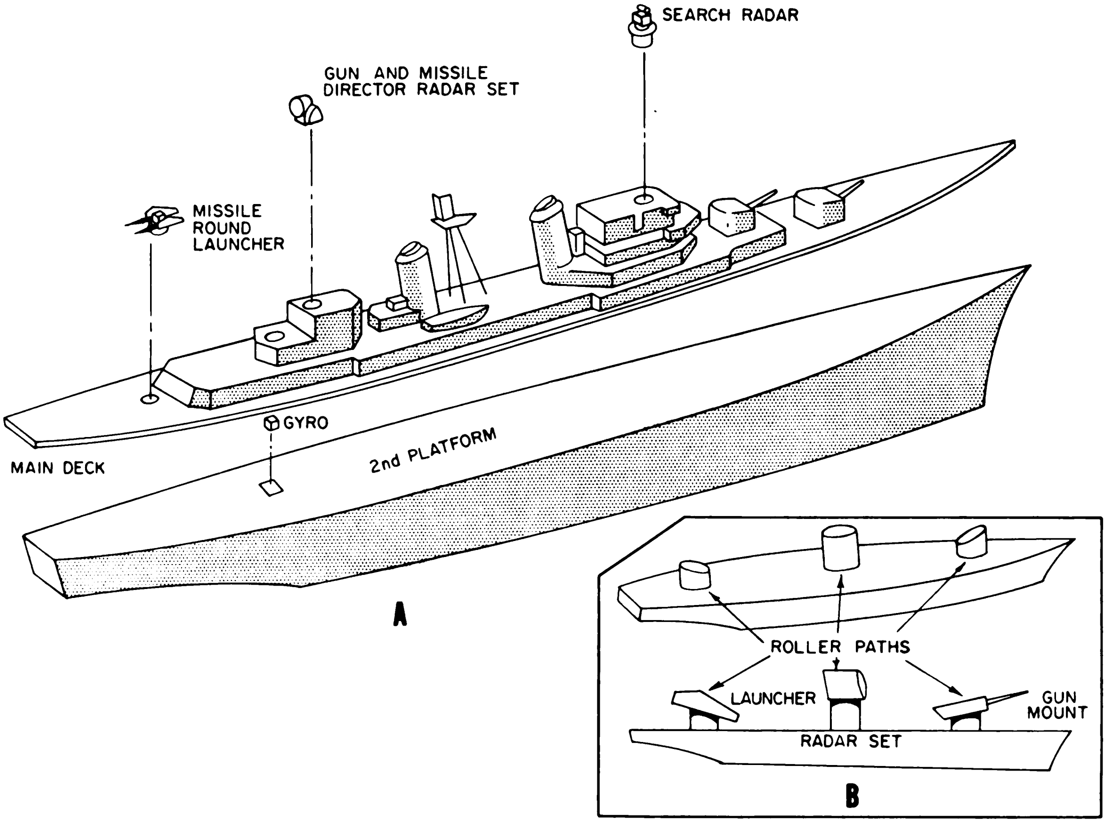


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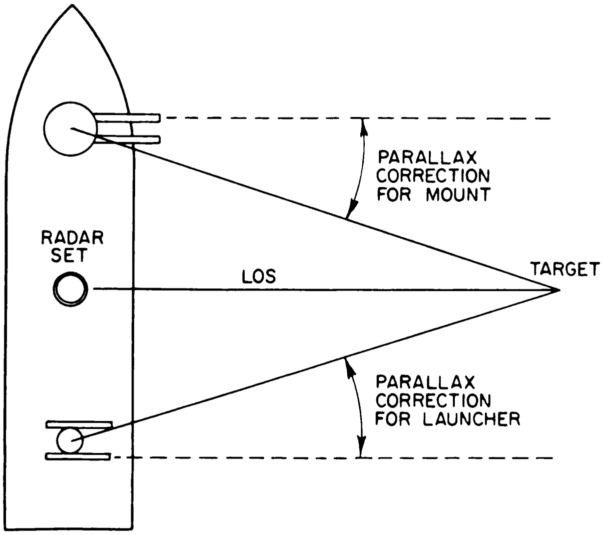
Figure 2-24.—Location of the foundations of the major weapon system elements.


PARALLAX CORRECTION FOR MOUNT
RADAR SET
LOS
TARGET
PARALLAX CORRECTION FOR LAUNCHER

12.48

Figure 2-25.—Horizontal parallax.

THE ANTIAIRCRAFT PROBLEM

The antiaircraft problem, sometimes called the air or AA problem, is another form or variation of the basic fire control problem. All of the factors that entered into the statement of the surface fire control problem must be considered in stating the air problem. The air problem is further complicated, however, by the essential difference between surface and air targets. The main difference between the two problems is the fact that the air target is moving at high speed ABOVE the surface of the ocean, and may be climbing or diving. Nevertheless, the air problem contains the three basic factors that we have previously considered in the discussion of the surface problem. These are (1) the line of sight, (2) the line of fire, and (3) the lead or prediction angle.

AIR TARGETS COMPARED TO SURFACE TARGETS

Air targets are generally faster than surface targets. Surface targets seldom have speeds greater than fifty knots, whereas many aircraft have cruising speeds so great that they are indicated by Mach numbers instead of knots.

If projectiles traveled at the speed of electromagnetic radiation (186,000 miles per second), the solution of the fire control problem would be greatly simplified. But projectiles require a definite time to reach a target. If time of flight is short, and a slow surface target is involved in the problem, the chances of hitting the target are good. On the other hand, a fast air target with good maneuverability may be able to get out of the predicted impact area during the time of flight of the projectile. Thus the probability of a kill is greatly reduced.

Surface targets as a general rule are larger than air targets. This obviously makes a surface target easier to see and to track.

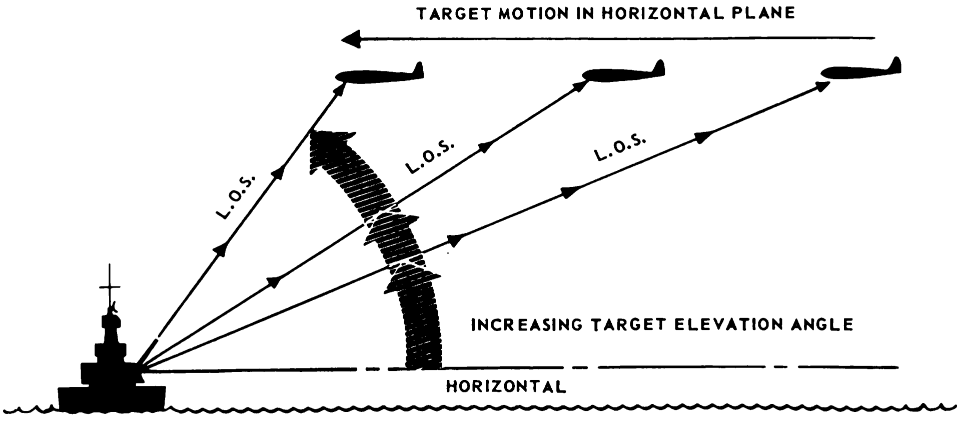
Accurate target motion information greatly increases the probability of a target kill. Because of their high speed and small size, aircraft targets are exceedingly difficult to see and to track.

In the surface problem the target and own ship are assumed to be in the horizontal plane. Therefore, the target elevation angle (the angle between the LOS and horizontal) is zero. Air targets, however, are ordinarily well above the earth's surface, so that the LOS makes an appreciable angle with the horizontal plane. In addition, if the target is approaching or leaving own ship, the LOS must be elevated or depressed to keep the target in view. Thus target elevation angle continually increases and decreases as the target maneuvers. You can see the effect of a moving air target on target elevation angle in figure 2-26.

To prevent complicating the basic air problem, we will discuss it in its simplest form just as we did in stating the surface problem. We will use a fixed gun employing a simple gun sight firing at a stationary air target to form a basis for the discussion.

Look at figure 2-27. It should look familiar to you. In fact it is almost identical to figure 2-14. But there is one important difference between the two illustrations. In figure 2-27 notice that there are two planes. The one marked HORIZONTAL PLANE you are familiar with. But the one labeled SLANT PLANE introduces a new term. In figure 2-27 the line of sight to the target is not in the horizontal as it is in figure 2-14, but in the slant plane which passes through the gun trunnion axis. Figure 2-27 shows that the slant plane is produced because the target (therefore the LOS) is now elevated instead of lying in the horizontal. Notice too that sight angle and sight deflection are measured in respect to the line of sight just as they were in the surface problem. But with the introduction of the slant plane these two fundamental angles must be redefined in terms of the slant plane. First, you should clearly understand the planes shown in figure 2-27 so that the significance of these two very important angles may be understood. Now let's define these two angles.

SIGHT ANGLE is the angle between the gun bore axis (LOF) and the slant plane. The slant plane contains the line of sight. The angle is measured in a plane perpendicular to the trunnion axis and passing through the gun bore. SIGHT DEFLECTION is the angle by which the plane through the gun bore is deflected from the


TARGET MOTION IN HORIZONTAL PLANE
L.O.S.
L.O.S.
L.O.S.
INCREASING TARGET ELEVATION ANGLE
HORIZONTAL

12.16

Figure 2-26.—Effect of moving air target on elevation angle.

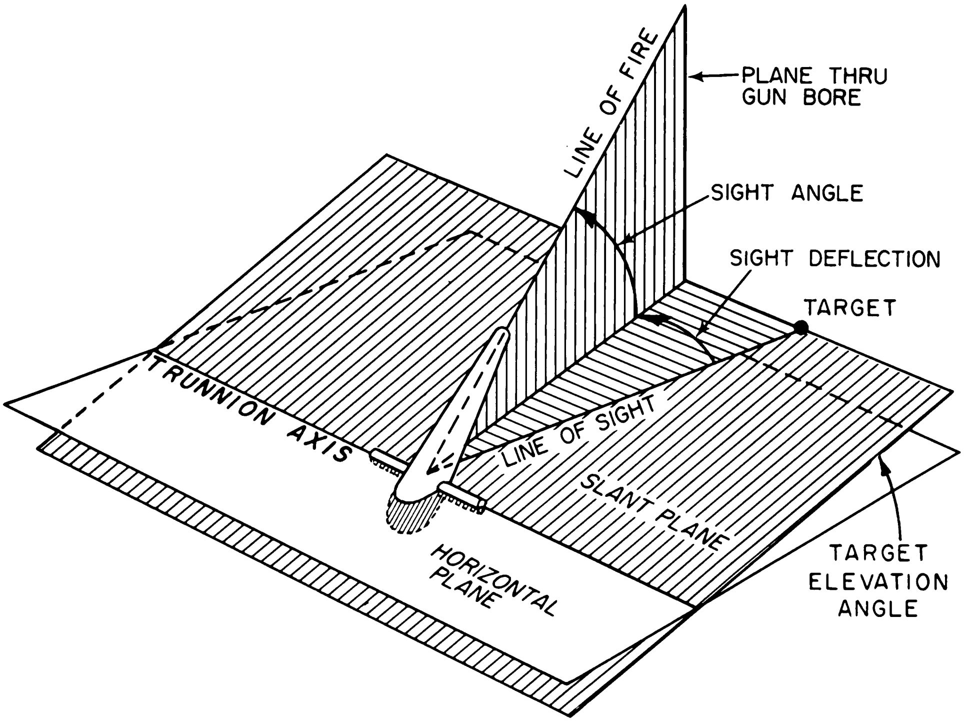


Figure 2-27.—Sight angle and sight deflection in the air problem.

line of sight. This angle is measured in the slant plane.

All the factors that entered into the statement of the surface problem must be considered in the air problem. A line of sight must be established, and a prediction angle must be formed in order to fix the line of fire. The forces and motions which influence the trajectory of a projectile are the only ones that we must consider if an air target is stationary. Of course, if the target were moving we would have to consider the effects of relative motion. But this is not the case here. Both target and ship are stationary, therefore the prediction angle is made up entirely of corrections for ballistic effects.

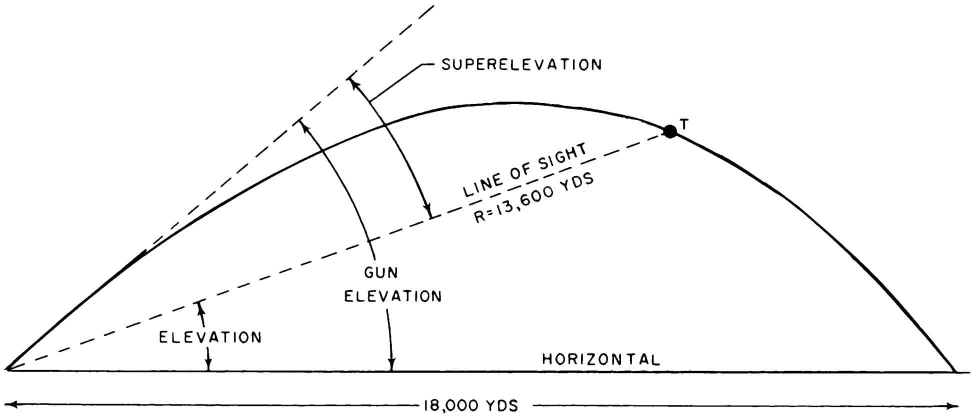
AA BALLISTICS FOR STATIONARY TARGETS

In figure 2-28, point T represents a stationary air target. Suppose you set your sights on the target and find they are elevated 20° above the horizontal. This angle, target elevation above the horizontal, also called position angle, is labeled in the figure. In the illustration the distance to the target is 13,600 yards. This distance is the slant range R. Remember that the line of sight is in the slant plane. Thus the term slant range.

Now suppose you find that, if you elevate the gun 40° above the horizontal, the projectile will hit the target, (neglecting drift and other deflection effects for the moment). However, if you look at a 5-inch range table, you will find that a range of 18,000 yards corresponds to the angle of departure of 40 degrees. This means that the trajectory of the shell touches the horizontal plane at a distance of 18,000 yards if the angle of departure is 40 degrees.

Using the same combination of mathematics and experiment by which the 18,000-yard figure was obtained, ballistic experts can calculate the distance from the gun at which the trajectory cuts a plane sloping upward at 20°—in this case 13,600 yards—or a plane sloping upward at any other angle.

Standard range calculations produce a range table showing the angles of departure corresponding to different horizontal ranges. Similar calculations, therefore, can produce a "slant range" table showing the angles of departure corresponding to various slant ranges at 20° elevation of the LOS. Thus, in figure 2-29 a gun elevation of 24° will give you a slant range of 6000 yards at 20° target elevation. For 8,000 yards you need 26° 30', and so on. From such



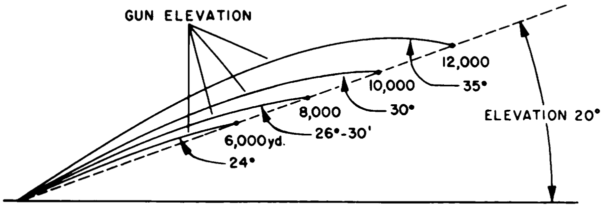
12.18

Figure 2-28.—An AA trajectory.

a table you could tell the elevation of the gun above the horizontal that would be required to hit any target of known range and 20 elevation. To be useful, of course, such a table would have to be made up for all target elevations.

However, as a practical matter, you don't think in terms of elevating the gun above the horizontal. You elevate it above the LOS. In local gun control, you set the sight angle onto the gunsights and then keep the sights on the target. The angle required is therefore the angle of gun elevation above the line of sight. This angle is called superelevation, and is illustrated in figure 2-30. Briefly, superelevation is the angle the gun must be elevated above the predicted target elevation to allow for curvature of the trajectory in a vertical plane. It increases as range increases and decreases as elevation increases.

In the case of a motionless target and standard conditions, superelevation is equal to sight angle. It should be clear that the gun cannot be pointed directly at the target because the pull of gravity on the projectile during the time of flight will cause the trajectory to curve downward.



12.19

Figure 2-29.—Range and superelevation.

The other two ballistic factors, wind and drift, affect the projectile's trajectory much the same as they do in the surface problem, and will not be covered here.

Now that you are familiar with the problem involved in hitting a stationary elevated target, let's take a look at the more complex part—hitting a moving target, traveling at high speed. In stating this problem we must assume that the target does not change its velocity (speed and direction) during the time of flight of the projectile. In other words, the target flies in a straight line at a constant speed from the time

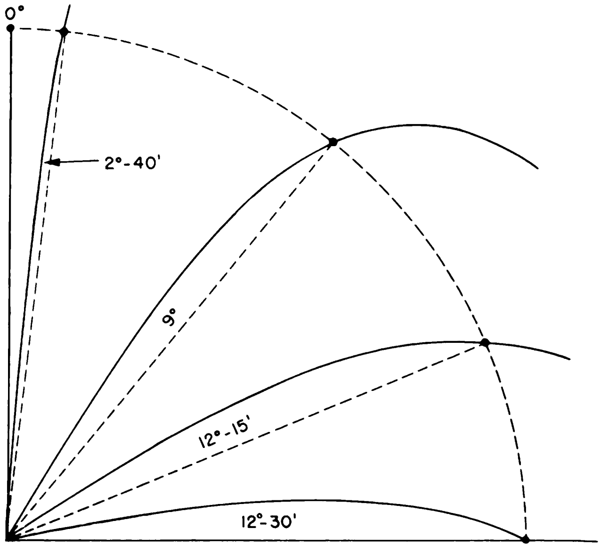


Figure 2-30.—Superelevation varies as the Cos of gun elevation.

12.20

the gun is fired until the projectile intercepts the target.

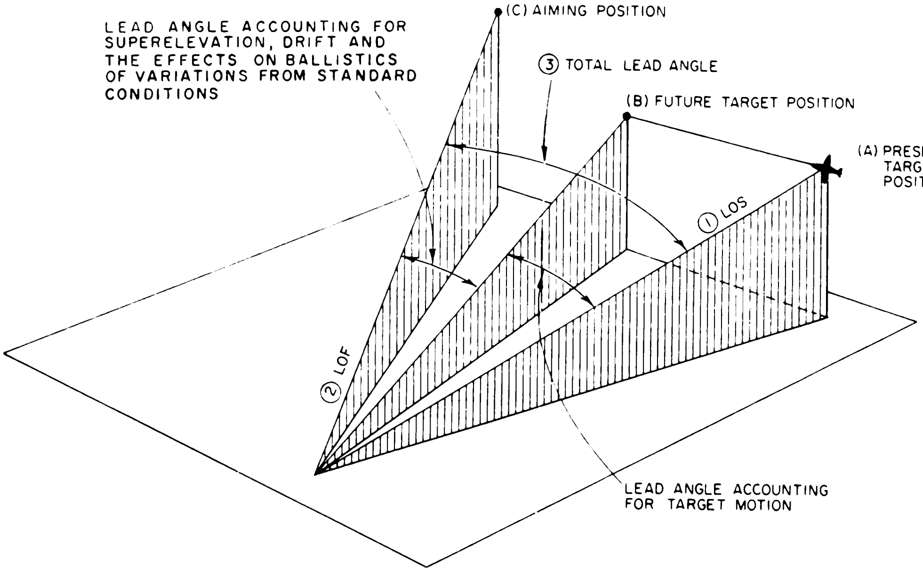
Also, in this part of the discussion, we will assume that the gun is stationary. It is true that relative movement of the gun platform with respect to the target affects the problem. But in the case of high speed targets the effect is negligible.

We can finish our study of the air problem, as it is seen from a gun, by discussing the geometrical diagram of the air problem shown in figure 2-31. Consider the target as being at the point labeled Present Target Position (A) at the instant of firing the gun. If you aimed and fired the gun at point (A) it is fairly obvious that the projectile would miss the target, because during the projectile's time of flight the plane would move from point (A) to point (B). Point (B) is called Future Target Position. It is defined as the position the target will occupy at the end of time of flight, or that point in space where the target and projectile will collide. You can see from this brief illustration that target motion has a miss-producing effect which must be corrected for.

If wind, gravity, drift, and other ballistic effects did not have to be compensated for, we could aim the gun directly at the future target position (B), fire the gun, and score a hit. In other words, if the projectile followed a straight line path from the gun to the point where the target will be at the end of the projectile's time of flight, we could not miss the target. But naval guns do not have straight line trajectories. True, trajectories are sometimes referred to as being flat, but the term flat is used in comparison to the trajectories of mortar shells and other projectiles having high arching flight paths. The fact remains that projectiles curve, and we must aim the gun ahead of the point designated as future target position. Therefore, let's choose another point in space at which to aim the gun so that the projectile will collide with the target at point (B). Locate point (C) in figure 2-31. This imaginary point in space is called the Aiming Position; it takes into account all the ballistics effects and the effect of target motion.

REPRESENTATIVE ANTIAIRCRAFT GUN SYSTEM

In truth it is difficult to select one system which is representative of all the types of AA gun fire control systems. Different systems have various distinctive features. Perhaps the major distinction is the method used to measure target motion. There are two methods used by shipboard systems. The first of these is the linear rate method. In this method the target's future position is based on computed linear rates of motion. The rates are normally computed about the tracking line (LOS). The second method is


(C) AIMING POSITION
LEAD ANGLE ACCOUNTING FOR SUPERELEVATION, DRIFT AND THE EFFECTS ON BALLISTICS OF VARIATIONS FROM STANDARD CONDITIONS
③ TOTAL LEAD ANGLE
(B) FUTURE TARGET POSITION
(A) PRESENT TARGET POSITION
① LOS
② LOF
LEAD ANGLE ACCOUNTING FOR TARGET MOTION

12.21

Figure 2-31.—The geometry of the air problem.

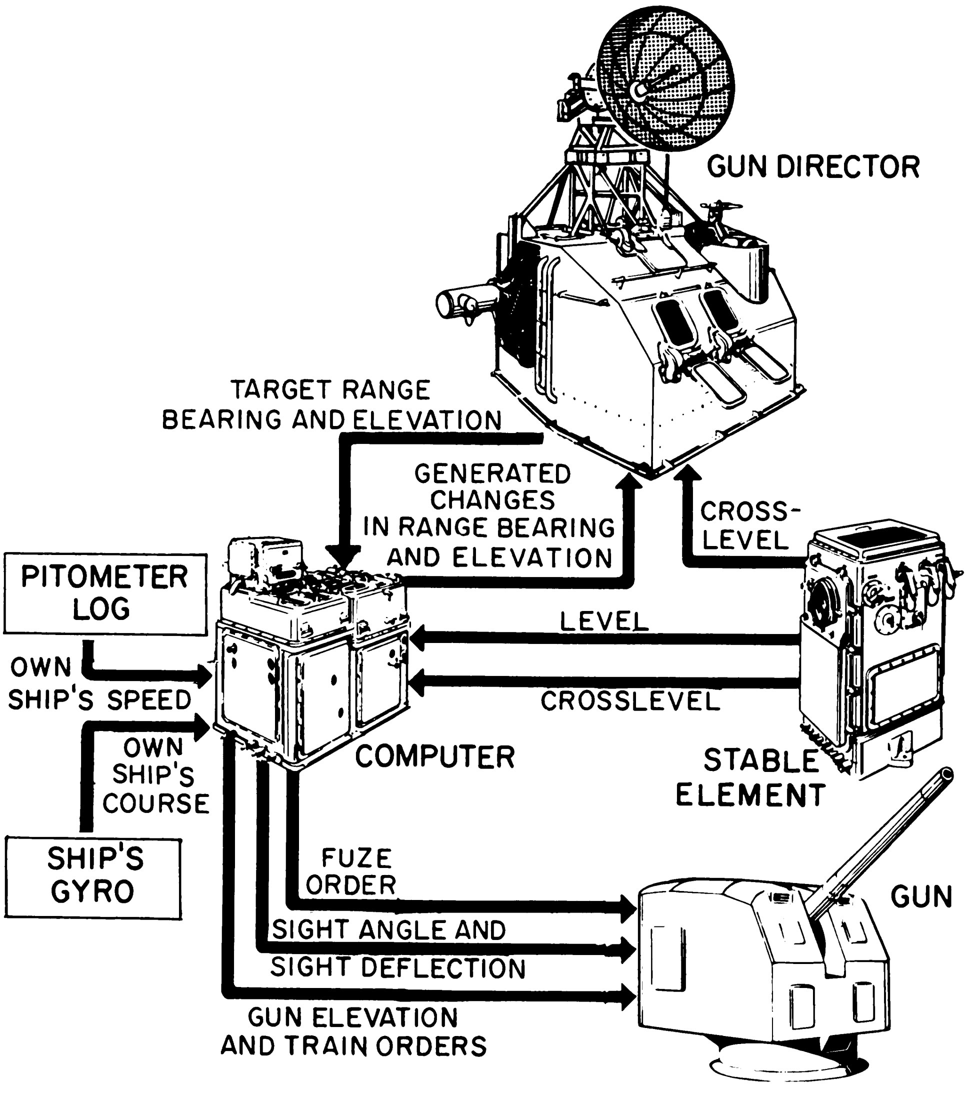
the angular or relative rate method based on the angular rate of motion of the tracking line. The basic fire control problem has broad application, and can be applied equally well to either method. Since an angular rate system is covered in chapter 10 of this course, we will associate the AA problem here with a linear rate system.

Gun Fire Control System Mk 37

Figure 2-32 is a simplified diagram of the Gun Fire Control System Mk 37. Notice the similarity of the data flow between this system and the surface system shown in figure 2-21. Fundamentally, the major units have identical functions. Therefore we will not dwell too long on the diagram.

The director measures target present position and transmits to the computer the range, bearing, and elevation of the target. The director tracks the target and provides the computer with continuous target position data.

The computer uses the target data and own ship's course and speed to set up a simulated relative motion problem within itself. In the


GUN DIRECTOR
TARGET RANGE BEARING AND ELEVATION
GENERATED CHANGES IN RANGE BEARING AND ELEVATION
CROSS-LEVEL
PITOMETER LOG
OWN SHIP'S SPEED
LEVEL
CROSSLEVEL
OWN SHIP'S COURSE
COMPUTER
STABLE ELEMENT
SHIP'S GYRO
FUZE ORDER
GUN
SIGHT ANGLE AND SIGHT DEFLECTION
GUN ELEVATION AND TRAIN ORDERS

12.262

Figure 2-32.—A simplified linear rate AA gun system.

simulated problem the computer calculates the linear rates of motion in range, bearing, and elevation. These rates are used in the generation of the relative motions in the simulated problem. The generated motions are transmitted to the director to aid in tracking the target in the actual problem. Simultaneously the rates are used to predict the relative motion which will occur during the projectile's time of flight. This amount of motion is added to the target's present position to obtain the future position. The computer uses the future position to calculate the ballistic corrections. The ballistic corrections are added to the predicted relative motion to obtain the lead angles: sight angle and sight deflection. The lead angles are in turn added to the present position of the target to obtain the aiming point as described by the gun orders.

The gun orders and the lead angles are transmitted to the gun. Notice the addition of fuze order to the gun. We will discuss fuze order separately. The train and elevation orders to to the gun mount's power drives. The power drives, when in automatic control, keep the gun pointed at the aiming point established by the computer. The lead angles are inputs to the sight-setting system to keep the gunsights in the LOS. The gun can be fired locally or from a remote station. Normally a remote station, the director, or plot, controls the firing circuit.

Due to the nature of an air target, a direct hit is improbable. Consequently the projectile is detonated by a fuze when it is within effective range of the target. The variable time fuze (Vt), commonly called the proximity fuze, will detonate the projectile automatically. The mechanical time fuze, however, requires a fuze setting to detonate. The time of flight of the projectile to the future target position at the instant of fire is transmitted to the gun as fuze order.

The stable element furnishes level and cross-level for stabilization. Thus it is functionally identical to the stable vertical in the surface system. Ship's roll and pitch motions are compensated for in both the LOS and the LOF. Level is sent to the director via the computer.

Parallax is not included in the diagram. The computer solves for horizontal and vertical parallax. The vertical parallax correction is included in gun elevation order. The horizontal parallax, however, is transmitted to the gun as a separate quantity.

GUN FIRE SUPPORT

During World War II, our fleet was the most proficient at the art of destroying land-based targets that the world had ever seen. Ships in all combat theaters fired missions using guns of all calibers at targets ranging from palm trees in the Pacific to tanks in Italy. These jobs were done efficiently and effectively. Naval gun fire support ships received high tributes from our Army, the Allied Forces, and even the enemy.

One captured German military journal stated: "The fire curtain provided by the guns of the U. S. Navy so far proved to be one of the best trump cards of the Anglo-United States invasion Armies. It may be that the part played by the Fleet was more decisive than that of the air forces because its fire was better aimed and unlike the bomber formations it had not to confine itself to short bursts of fire. . . . ."

The German leaders, Rommel, Von Runstedt, and Hitler, commented bitterly on the serious effect our naval gunfire had on the German defenses.

During the period from the end of World War II to the beginning of the Communst invasion of Korea, naval gun fire support deteriorated in performance. To some degree this skill was regained during the Korean crisis. It resulted from a good deal of practice, and the realization that the life of an American soldier or marine might well depend on a target hit in minimum time.

Today, only a few years later, we find that the gun fire support provided by the fleet does not meet the superior standards set by the ships that fought so gloriously in World War II and in Korea.

What has happened? In general, the ships now are equipped with essentially the same or improved guns and fire control systems. There are many reasons given for this reduction in performance—the rapid turnover of personnel, increased complexity of other new equipment, and emphasis on other fire control fields and activities. The latter reason is the one that you, as an FT, are most concerned with.

It may seem to you, if you are aboard ship or in Class A school, that more emphasis is generally placed on learning the ship-to-ship, antiaircraft or missile aspects of fire control than on the ship-to-shore phase. But never let this seeming overemphasis on other things lead you to consider that shore bombardment is of minor importance. If you want to become a well-rounded Fire Control Technician it is most important for you to gain an understanding of all the variations of the basic fire control problem, and shore bombardment is one of these.

Land targets at sea level can be treated in the same manner as a surface ship target. But a target that is above sea level must be compensated for in the fire control solution. Why this correction is required can be easily understood if you will remember that surface range tables assume that the point of projectile impact is in the horizontal plane. Figure 2-33 illustrates the errors that result when the range of a land target (A) is taken from a navigational chart and the target's elevation is not taken into account. You can see that the projectile will fall short and below the target.

Targets that are located on the far reverse slope of a hill or similar ground feature lying between the gun and target present another problem. This problem requires obtaining a trajectory which will clear the top of the hill and be steep enough to hit the target beyond. This problem and its solution are illustrated in figure 2-34. Trajectory (A) is produced by projectiles using standard service powder charges and is too flat. (B) is the trajectory which can be obtained by using reduced velocity powder charges. These reduced charges decrease the I.V. of the projectile. This required the gun to be elevated to attain the same range as a standard charge. The trajectory produced by this technique is high and has steep sides. (C) is the trajectory which can be obtained with standard service powder charges by increasing the range to the target. This method required the firing ship to change its position.

The primary purpose of this section has been to introduce you to the shore bombardment problem. You have seen that it is similar to the traditional ship-to-ship problem. Now let us turn our attention to the mission of naval gunfire in support of landing operations, and the advantages of naval gunfire for troop support. In addition, you will learn some of the terminology used in naval gunfire in general.

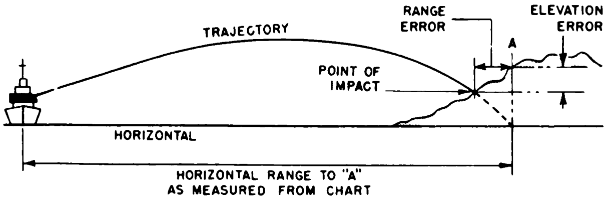


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Figure 2-33.—Errors resulting from failure to compensate for target elevation.

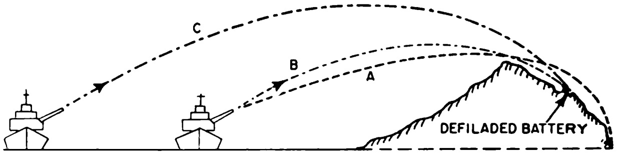

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Figure 2-34.—Problem of hitting a target on the reverse slope of a hill.

MISSION OF NAVAL GUN FIRE SUPPORT

The mission of naval gunfire in support of landing operations is to aid the seizure of the objectives by reducing or neutralizing shore installations and troops that oppose our forces prior to and during the landing, and by assisting the advance of our troops after the landing has been made. This support is vitally important in the period after the troops have landed but before adequate artillery can be brought into action. To be successful, naval gun fire support for amphibious operations must be carefully planned in advance, and must be executed with skill and dispatch. Full exploitation of support can be achieved only if ground, naval, and air personnel understand the organization, basic techniques, capabilities, and limitation of naval gun fire support, and follow the standard procedure which has been agreed upon by the joint services.

Naval gunfire is delivered from ship's batteries not only in support of troop operations, but of related naval and air operations, such as mine warfare activities, air-sea rescue operations, reconnaissance and demolition operations, demonstrations, feints, raids, flak suppression during air strikes, and interdiction of coastal roads, railroads, airfields, and troop assembly areas. All these activities rest on the same basic principles as the naval gun fire support of amphibious operations.

The basic task of naval gun fire support units in an amphibious operation is to support the seizure of the objective by destroying or neutralizing:

1. Shore installations that oppose the approach of ships and aircraft to the objective.
2. Defenses that may oppose the landing.
3. Defenses that may oppose the post-landing advance of the troops.

These tasks are carried out in the preparation of the landing, and postlanding support.

ADVANTAGES OF NAVAL GUNFIRE FOR TROOP SUPPORT

Naval gunfire has many capabilities for troop support in landings which are not possessed by artillery. The principal ones are:

1. AVAILABILITY. Gun fire support ships are continuously available before, during, and after the landing, as long as the zone of action ashore is within the range of the ship's guns.
2. MOBILITY. Within the limitations of navigation, ships can move rapidly from one area to another as the situation ashore develops. At the same time, the most favorable ranges and lines of fire can be fully exploited, and enemy counterfire can be evaded.
3. HIGH RATE OF FIRE. Power loading and mechanical ammunition supply makes it possible to deliver a large volumn of fire in a short time. This characteristic is of great value in neutralization missions.
4. HIGH MUZZLE VELOCITY AND FLAT TRAJECTORY. Naval guns, particularly those of heavy caliber, have great penetration and destructive power, especially against installations presenting vertical surfaces.
5. SMALL DEFLECTION PATTERN. The comparatively small dispersion in deflection of naval guns makes them valuable for close support of troops when the line of fire can be made parallel to the troops' front line (enfilade fire).
6. VARIETY OF WEAPONS AND TYPES OF AMMUNITION. Calibers of guns range from 20-mm to 8-inch, with ammunition of many types, including armor-piercing, fragmentation, and reduced-charge. Other available weapons include rocket and guided missile launchers, with a wide variety of ammunition types for each.

CLASSIFICATION OF GUNFIRE

You, and all the members of the fire control team, must know and understand the gunfire terms used during a support mission. Naval gunfire can be divided into five broad classifications, according to effect sought.

DESTRUCTIVE FIRE is deliberate and accurate gunfire to destroy a target. This fire requires a spotting group, takes considerable time, and uses large amounts of ammunition.

NEUTRALIZATION FIRE is rapid gunfire covering an area to prevent enemy fire, movement, or action. Although destruction may result, this is not the primary purpose of neutralization fire. Usually, neutralization has a temporary effect and the target may become active soon after neutralization fire ceases.

HARASSING FIRE is sporadic gunfire delivered during relatively quiet periods to prevent enemy rest, recuperation, and movement, and to lower enemy morale and efficiency.

ILLUMINATION FIRE is the use of star shells to illuminate the enemy area to permit early detection of enemy movements, to aid observation, and to facilitate own troop movement.

INTERDICTION FIRE is sporadic gunfire, of less intensity than neutralization fire, laid down on lines of communication to disrupt or intermittently deny their use to the enemy.

Methods of Delivery

Fire can be delivered, as mentioned before, in either of two ways: when the target is visible and can be used as a point of aim—DIRECT FIRE, and when the target is not visible or is not used as a point of aim—INDIRECT FIRE.

Additional Classification of Gunfire

The five general classes of gunfire are further subdivided according to tactical uses, types of fire, techniques of delivery, and degree of prearrangement.

Tactical Uses

Tactical uses of gun fire support are as follows:

CLOSE SUPPORTING FIRE is gunfire delivered on targets within 600 yards of friendly forces.

DEEP SUPPORTING FIRE is gun fire delivered on targets farther than 600 yards from friendly forces.

PREPARATION FIRE is a heavy volume of prearranged gunfire delivered just prior to an attack by friendly forces on enemy-held positions.

COUNTERBATTERY FIRE is fire delivered against active enemy weapons and/or fire control stations.

RECONNAISSANCE FIRE is fire delivered in areas where camouflaged positions are suspected or in vital areas where natural cover prevents observation and/or gathering of photo intelligence.

FLAK SUPPRESSION is fire used to suppress AA fire immediately prior to, and during, an air attack on enemy positions.

CALL FIRE is fire on enemy targets delivered at the request of some spotting agency. (The spotting agency may be an air spotter, a member of a naval gun fire team ashore, or a member of a naval gun fire team offshore. Call fire missions are not interrupted without permission from the unit requesting the fire, except in case of an emergency.)

OPPORTUNITY FIRE is fire delivered on newly discovered targets, or upon targets of a transitory nature, without any formal planning or troop request. Targets of opportunity may present themselves at any time to the firing ship, but fire must be delivered with due regard for the safety of friendly troops. Ships delivering fire on targets of opportunity in close proximity to own troops require the approval of the troop echelon concerned before opening fire. Ships executing deep supporting fire must assure themselves that the target of opportunity is within their assigned zone of responsibility.

Types of Fire

Types of fire include the following:

AREA FIRE is a volume fire delivered in a prescribed area. Area fire is generally neutralization fire.

PRECISION FIRE is used for registration (to obtain corrections for increasing accuracy of subsequent fires), and for attack and destruction of point targets.

DEFILADE OR REVERSE SLOPE FIRE is delivered against targets located over a hill or ridge. Due to the flat trajectory of high-velocity naval projectiles, the hill or ridge may mask the target. In such a case, reduced powder charges are used, or the range is opened.

ENFILADE FIRE is delivered on a target in such a manner that the range pattern of the fall of shot aligns with the long axis of the target.

Techniques of Delivery

There are two techniques of delivery: direct fire and indirect fire.

DIRECT FIRE is gunfire delivered on a target, using the target itself as a point of aim for either the guns or the director. The fall of shot usually is spotted from the ship.

INDIRECT FIRE is gunfire delivered on a target although the target itself is not used as a point of aim for laying the guns or the director. (The various methods of indirect fire will be covered later.) Indirect fires are spotted by air spotters or shore fire control party spotters.

Degree of Prearrangement

Prearranged fire is scheduled fire delivered on known or suspected targets in accordance with a planned schedule either on a time or on a call basis.

This fire is delivered against enemy beach defenses whose presence is known from prior reconnaissance and intelligence, or is suspected from a study of the landing beach and adjacent areas. Since not all of the enemy defenses will have been located previously, provision is made for shifting from prearranged fire to targets of opportunity if their relative importance warrants.

CHAPTER 3

THE GUIDED MISSILE

INTRODUCTION

This chapter is a brief discussion of the physical and functional characteristics of the guided missiles that the FTM will encounter. The information is presented at an elementary level to introduce the FTM to the guided missile.

Many of the missile's guidance devices introduced in this chapter will be covered in detail later on in the course. After you have studied the remainder of the course, come back and review this chapter.

WHAT IS A GUIDED MISSILE

A MISSILE may be defined as ANY object capable of being hurled, thrown, projected, or propelled, so as to strike a distant object. An UNGUIDED MISSILE is a missile which is AIMED but which CANNOT CONTROL its own trajectory or flight path. A thrown rock is an example of an unguided missile. A GUIDED MISSILE is a missile whose trajectory IS CONTROLLED during all or part of its flight, by mechanisms within the missile. A ROCKET is a missile which carries a propulsion system that IS NOT DEPENDENT on the oxygen in the atmosphere. Thus, the term MISSILE is a general one. The term ROCKET is specifically limited to missiles carrying air-independent propulsion systems.

A GUIDED MISSILE is defined as an unmanned vehicle moving above the earth's surface, whose trajectory or flight path is capable of being altered by a mechanism within the vehicle.

MISSION OF GUIDED MISSILES

Guided missiles were developed to overcome the limitations of older weapons. The development of conventional weapons has reached a point where tremendous cost and effort are necessary to produce only a small improvement in their performance. The primary mission of a guided missile is the same as that of its counterpart, the conventional weapon. The following examples show some of the missions and the advantages of using guided missiles to supplement or replace them.

Air-to-surface guided missiles are greatly superior to conventional bombs. The aircraft dropping bombs is limited in the performance of its mission by weather, interception by enemy aircraft, antiaircraft artillery, and, in some cases, the maneuvering of the target during the fall of the bombs. By building bombers that can fly higher and faster, antiaircraft artillery and fighter interception can be evaded; but the accuracy of the bombs would be greatly reduced, and the weather would have a greater effect. By replacing the bombs with guided missiles which can be launched at greater ranges and which contain a guidance system that will home on the target regardless of weather and target maneuvers, the destructive effect can be greatly increased, and the danger of enemy countermeasures greatly reduced. The effectiveness of this type of guided missile is illustrated by the following incident which occurred during World War II in the Pacific.

Two Navy patrol planes sighted two ships 20 miles away by radar. They went in close enough to identify them visually as Japanese destroyers and were met with heavy antiaircraft fire at a range of 8 miles. When the planes turned away and were out of range, the Japanese stopped firing. One plane then returned and launched a guided missile (named the Bat) from outside the antiaircraft range. The missile sped straight for the leading destroyer and blew off her bow. The other destroyer rushed to her aid, throwing futile antiaircraft fire in the direction of the attacking plane, which was out of range. The Japanese probably did not understand the true nature of the flying bomb, which struck with little or no warning after being launched from planes flying at what normally would be considered safe ranges.

This leads us to the FT side of the problem, the surfaced-launched guided missile. Obviously, we want the operational capabilities of our ship's weapons to exceed those of the enemy. An aircraft, for example, must be destroyed before it reaches its weapon-release range, called its standoff range. The ship-launched guided missile is greatly superior to the gun, in range, maximum altitude and accuracy, and therefore can destroy an enemy aircraft beyond the range of a gun.

Aircraft are used to overcome the range limitations of naval gunfire. But aircraft are hampered by enemy air coverage, antiaircraft artillery, and weather. Long-range, supersonic guided missiles, however, can be launched from ships to bombard enemy installations. These surface-to-surface missiles have guiding devices that are not affected by weather, and their trajectory and velocity make them practically invulnerable to conventional defense weapons.

CLASSIFICATION OF GUIDED MISSILES

Guided missiles are widely known by their popular names, such as Terrier, Talos, and Polaris, but every missile is assigned a designation consisting of letters and numerals which classifies and identifies it within the guided missile weapon family. When guided missiles were introduced, the Navy developed its own designation system. Since then a uniform servicewide designation system has been accepted. The former system will not disappear from use in the immediate future; therefore, it is listed in the table used to explain the newer designation system.

Designation System

The new designation system indicates the launch environment (where launched and from what type of launching device), mission, delivery vehicle type, design number, and series symbol of the missile. The table (fig. 3-1), explains the new designations, and lists the Navy missiles and rockets with their current and former designations. New missiles and rockets are assigned the next consecutive design number within the appropriate basic mission.

A design number is assigned to each type of missile, with the number "1" assigned to the first missile of each type. For example, all five modifications of the Terrier missile (BW-0, BW-1, BT-3, BT-3A, and HT-3) have the design number "2". Tartar missile modifications (Basic and Improved Tartar) have the design number "24" which indicates it is the 24th type RIM developed.

To distinguish between modifications of a missile, series symbol letters beginning with "A" are assigned. Therefore, the Terrier BW-0 has been assigned the symbol letter "A", and the Terrier BW-1 has been assigned the symbol letter "B". The series symbol letter follows the design number. Incidentally, to avoid confusion between letters and numbers, the letters "I" and "O" will not be used.

If necessary, a prefix letter is included before the military designation. A list of applicable prefix letters is shown at the bottom of the table (fig. 3-1).

Navy missiles are assigned mark (Mk) and modification (Mod) numbers. These numbers and the name of the missile are normally used in Navy publications. Missiles having two-stage propulsion systems (separate boosters), for instance the Terrier and Talos, have one Mk and Mod number for the complete round. The missile and the booster sections however, have their own mark and modification numbers.

COMPONENTS OF GUIDED MISSILES

All guided missiles must contain certain components in order to perform their mission. The missile must have a body or basic structure; it must be propelled; it must be guided; and it must carry a payload. The principal structure of the missile, which houses the other components, is called the AIRFRAME. The component which moves or propels the airframe is the PROPULSION SYSTEM, or power plant. The component which makes the vehicle a true guided missile is the GUIDANCE AND CONTROL section. Further, if the missile is to perform a useful military mission, it must contain a payload consisting of a WARHEAD AND FUZES.

Various types of these components are discussed here to serve as a basis for your future study, and many of the terms applied to guided missiles are introduced.

NAVY MISSILE AND ROCKET DESIGNATIONS

Reprinted from Naval Aviation News, September 1963

LAUNCH ENVIRONMENT SYMBOLS

Letter	Title	Description
A	Air	Air launched.
B	Multiple	Capable of being launched from more than one environment.
C	Coffin	Horizontally stored in a protective enclosure and ground-launched.
H	Silo Stored	Vertically stored below ground level and launched from the ground.
L	Silo Launched	Vertically stored and launched from below ground level.
M	Mobile	Launched from a ground vehicle or movable platform.
P	Soft Pad	Partially or nonprotected in storage and launched from the ground.
R	Ship	Launched from a surface vessel, such as ship, barge, etc.
U	Underwater	Launched from a submarine or other underwater device.

MISSION SYMBOLS

Letter	Title	Description
D	Decoy	Vehicles designed or modified to confuse, deceive, or divert enemy defenses by simulating an attack vehicle.
E	Special Electronic	Vehicles designed or modified with electronic equipment for communications, countermeasures, electronic radiation sounding, or other electronic recording or relay missions.
G	Surface Attack	Vehicles designed to destroy land or sea targets.
I	Intercept-Aerial	Vehicles designed to intercept aerial targets, defensive or offensive.
Q	Drone	Vehicles designed for target, reconnaissance, or surveillance purposes.
T	Training	Vehicles designed or permanently modified for training purposes.
U	Underwater Attack	Vehicles designed to destroy enemy submarines or other underwater targets or to detonate underwater.
W	Weather	Vehicles designed to observe, record, or relay meteorological data.

VEHICLE TYPE SYMBOLS

Letter	Title	Description
M	Guided Missile	Unmanned, self-propelled vehicles designed to move in a trajectory or flight path all or partially above the earth's surface and whose trajectory can be controlled remotely or by homing systems, or by inertial and/or programmed guidance from within. This term does not include space vehicles, space boosters, or naval torpedoes, but does include target and reconnaissance drones.
N	Probe	Non-orbital instrumented vehicles not involved in space missions that are used to penetrate the aerospace environment and report data.
R	Rocket	Self-propelled vehicles without installed or remote control guidance mechanisms, whose trajectory cannot be altered after launch.

Popular Name	Current Designation	Former Designation
	Missile Series	
Terrier BW-0	RIM-2A	SAM-N-7
Terrier BW-1	RIM-2B	SAM-N-7
Terrier BT-3	RIM-2C	SAM-N-7
Terrier BT-3A	RIM-2D	SAM-N-7
Terrier HT-3	RIM-2E	SAM-N-7
Regulus I	RGM-6A	SSM-N-8
Regulus I	RGM-6B	SSM-N-8A
Regulus I	BQM-6C	KDU-1
Sparrow I	AIM-7A	AAM-N-2
Sparrow II	AIM-7B	AAM-N-3
Sparrow III	AIM-7C	AAM-N-6
Sparrow III	AIM-7D	AAM-N-6A
Sparrow III	AIM-7E	AAM-N-6B
Talos (6B)	RIM-8A	SAM-N-6B
Talos (6BW)	RIM-8B	SAM-N-6BW
Talos (6B1)	RIM-8C	SAM-N-6B1
Talos (6BW1)	RIM-8D	SAM-N-6BW1
Talos (6BC1)	RIM-8E	SAM-N-6C1
Talos	RIM-8F	SAM-N-6B1(CW)
Sidewinder I	AIM-9A	AAM-N-7
Sidewinder 1A	AIM-9B	AAM-N-7
Sidewinder IC-SAR	AIM-9C	AAM-N-7
Sidewinder IC-IR	AIM-9D	AAM-N-7
Bullpup	AGM-12A	ASM-N-7
Bullpup	AGM-12B	ASM-N-7A
Bullpup	AGM-12C	ASM-N-7B
Bullpup Trainer	ATM-12A	ASM-N-7 (Martin-Marietta)
Bullpup Trainer	ATM-12B	ASM-N-7A (Maxson)
Regulus II	RGM-15A	SSM-N-9
Regulus II	MQM-15A	KD2U-1
Hawk	MIM-23A	M-3
Tartar Basic	RIM-24A	SAM-N-7
Tartar Improved	RIM-24B	SAM-N-7
Polaris A1	UGM-27A	
Polaris A2	UGM-27B	
Polaris A3	UGM-27C	
Firebee	BQM-34A	Q2C
Firebee	AQM-34B	KDA-1
Firebee	AQM-34C	KDA-4
	MQM-36A	KD2R-5
	AQM-37A	KD2B-1
	AQM-38B	RP-78
	MQM-39A	KDB-1
	XQM-40A	KD6G-2
Petrel	AQM-41A	AUM-N-2
Redeye	XMIM-43A	
SUBROC	UUM-44A	
Shrike	AGM-45A	ASM-N-10
Sea Mauler	RIM-46A	
	RIM-50A	SAM-N-8
Condor	AGM-53A	ASM-N-11
Phoenix	AIM-54A	AAMN-11
	RIM-55A	SAM-N-9
	PQM-56A	CT-41
	ZRGM-59A	
	Rocket Series	
Honest John	MGR-1B	M-50
Weapon Alpha	RUR-4A	
ASROC	RUR-5A	

STATUS PREFIX SYMBOLS

J	Special Test (Temporary)	Vehicles especially configured simply to accommodate test.
N	Special Test, (Permanent)	Vehicles so modified they will not be returned to original use.
X	Experimental	Vehicles under development.
Y	Prototype	Reproduction vehicles for test.
Z	Planning	Vehicles in planning stage.

February 1964 DIGEST

Figure 3-1.—Navy missile and rocket designations.

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AIRFRAMES

The airframe of a guided missile consists of the body of the weapon and the airfoils which stabilize it in flight and control its path. The missile airframe serves the same purpose as the airframe of an airplane: it carries the necessary components and determines the flight characteristics of the vehicle.

In most missiles the main body is a slender, cylindrical structure. Several types of nose sections are employed (fig. 3-2). If the weapon is intended for speeds exceeding that of sound, the forward section usually has a pointed-arch profile in which the sides taper in lines called "ogive" curves. In missiles which fly at lesser speeds, the nose is frequently less sharp or is even blunt. In some, the forward end is covered by a rounded radome (the housing for a radar antenna); in others, the nose section contains the opening which forms one end of the duct required for the jet power system.

Typical airframes contain a main body which terminates in a flat base. When the contour is slightly streamlined at the rear, the missile is said to be "boattailed." Attached to the body are one or more sets of airfoils, which provide lift in some cases, and which control the flight path and increase the stability. The basic types of design which are employed in missile airframes are distinguished principally by the location of the control surfaces with respect to the missile body. These types are the CANARD, the WING-CONTROL, and the TAIL-CONTROL designs, (fig. 3-3).

For canard airframes, small control surfaces are placed forward of the center of gravity, the point at which the total mass of the body can be considered as being concentrated. Fixed fins, larger than the control surfaces, are mounted on the tail section to increase flight stability.

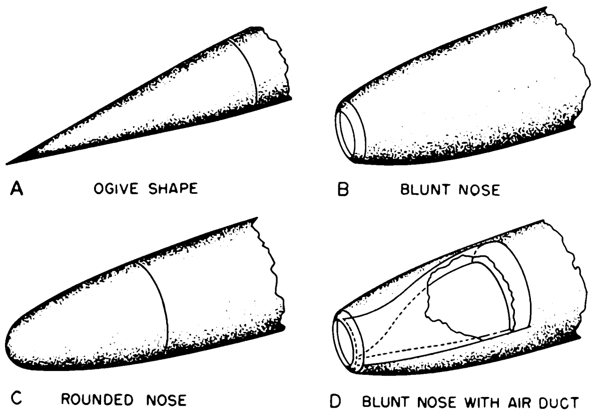

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Figure 3-2.—Missile noses.

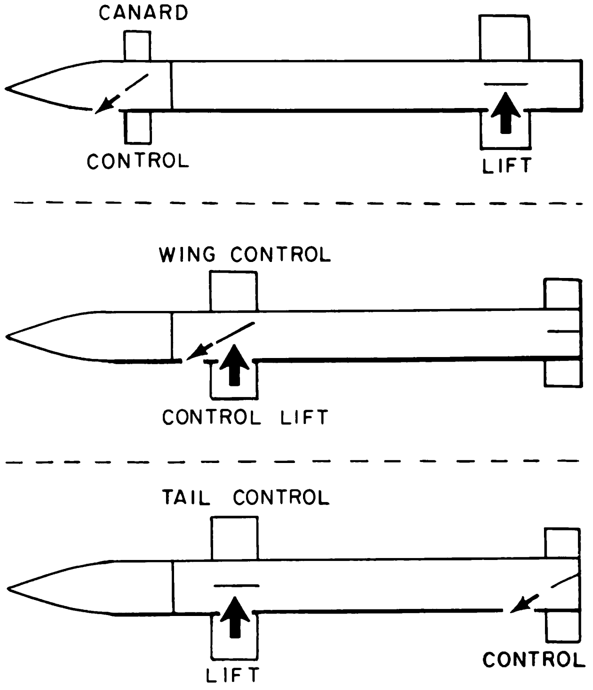

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Figure 3-3.—Missile airframe design with respect to control surface locations.

In the wing-control design, the control surfaces are mounted at or near the center of gravity. Larger than in the canard arrangement, the controlling surfaces also provide considerable lift; and fixed fins are mounted at the tail section of the missile body. In the tail-control configuration, the control surfaces are placed at the rear of the airframe. If wings are included, they are mounted amidships and contribute lifting force but do not control the flight path.

The fuselages of many of the larger guided missiles, such as the surface-to-surface weapons, resemble those of modern aircraft in construction, being based on the SEMI-MONOCOQUE structure which is widely used in conventional airframes. The semimonocoque fuselage (the word "monocoque" means "one shell") consists of a metal skin or shell which is internally braced. The strength of the body is provided mainly by the shell, which is reinforced by inner bulkheads, called FRAMES, and longitudinal braces, called STRINGERS.

In some missiles, the body is made up of several sections. Each section is a cylindrical shell rather than a built-up structure. Each body shell contains one of the essential units or components of the missile, such as the propulsion system, the electronic control equipment, the warhead, or the fuze assembly.

Sectionalized construction has the advantage of strength with simplicity and also provides ease in replacement and repair of the components since the shells are removable as separate units. The sections are joined by various types of connections which can be easily made or unmade. An example is the so-called BREECH-LOCK connection, in which the shells contain machined, interrupted threads, allowing the body sections to be joined by making an eighth of a turn. Access ports are usually provided in the walls through which adjustments of the inner components can be made.

PROPULSION SYSTEMS

In order to be an effective military weapon, a guided missile must move at a high speed. It must do so in order to better its chances of intercepting enemy missiles or aircraft when used defensively, and to decrease its changes of being intercepted when used offensively. Missiles are moved in a desired direction and at a desired speed in response to applied forces. These forces are produced by the propulsion system (power plant). The purpose of this section is to discuss briefly the means available for propelling guided missiles.

Principles of Jet Propulsion

Jet-propulsion systems are referred to as REACTION MOTORS because they operate on the reaction principle. This principle was stated first in Sir Isaac Newton's third law of motion, which says that for every action there is an equal and opposite reaction. This means that if a man pushing a car exerts a force of 150 pounds on the car, the car exerts an equal and opposite force of 150 pounds on the man. This principle, which reveals that all changes in motion are the result of applied forces and their reactions, is applicable to all types of motors as well as to jets.

In the propeller-driven aircraft, a certain weight of air passes through the propeller blades in a given amount of time. The action of the propeller increases the velocity of this weight of air in a direction opposite to that of the motion of the aircraft. Some force must act on the air in order to accelerate it rearward because all motion is the result of applied forces. The propeller, driven by the engine, supplies the motive force necessary to increase the momentum of the air, and the equal and opposite force, or reaction, is the thrust which moves the aircraft through the air. The air passes around the aircraft, however, and is not ejected from within the motor. In jet propulsion, matter is increased in momentum and ejected from WITHIN the motor. This fact makes jet propulsion different from other forms of propulsion.

The principle of jet propulsion is well illustrated when a man fires a rifle from his shoulder and immediately feels the kick, or recoil. This kick is the equal and opposite reaction to the force which ejected the bullet from the muzzle of the rifle. The bullet is the ejected matter, and the force which accelerates it from zero velocity to about 2,700 feet per second is the unbalanced pressure force created by the explosion of the powder. If the man stood on frictionless skates and fired several shots in rapid succession, the kick, or reaction, would propel him in a direction opposite to that of the bullets, or ejected matter.

One type of jet motor, the rocket, is very similar to the rifle or any naval gun. A combustion chamber corresponds to the cartridge case in the rifle; a nozzle corresponds to the muzzle of the rifle; and the molecules of gases of combustion correspond to the bullets of the rifle, illustrated in figure 3-4. When the rifle is fired, powder is burned and gases are generated at high temperature and pressure.

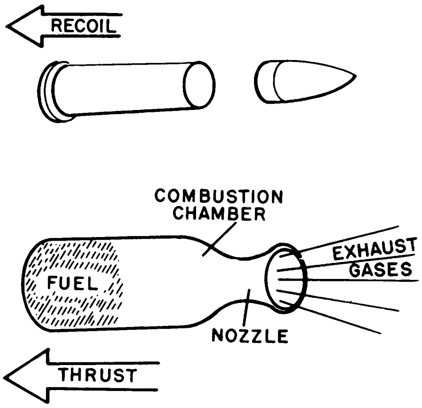

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Figure 3-4.—Principle of jet propulsion.

These gases will try to expand in all directions with the same force. But, because the cartridge case prevents expansion in all directions except toward the muzzle, the gases can only escape by pushing the bullet out of the barrel. In the rocket, fuel is burned in the combustion chamber and a large volume of gases is generated at high temperature and pressure. Since there is no bullet to push out of the way, as in the rifle, these gases escape through the nozzle at an extremely high velocity—about 5,000 feet per second. The reaction (recoil) of the rifle is very short in duration because only a small amount of powder is burned in a very short time. In the rocket, however, fuel is burned for a much longer time, and the ejection of billions of molecules of gases causes a sustained reaction which is the THRUST of the rocket.

This discussion shows that the reaction which propels a jet engine occurs WITHIN the engine, and does not occur as the result of the exhaust gases pushing against the air. (It also points up the fact that the principles of interior gun ballistics are generally applicable to missile propulsion systems.)

A gun fired in a vacuum would recoil with almost the same force as it does when air is present. Similarly, a jet-propelled missile—provided it carries the oxidizer necessary for the combustion of the fuel—would operate in a vacuum, under water, or at a very high altitude. In fact, a rocket motor reaches its most efficient operation in a vacuum. The opposite is true of propeller-driven vehicles because the forward push, or thrust, is dependent upon the air for the resisting force.

Classification of Thermal-Jet Motors

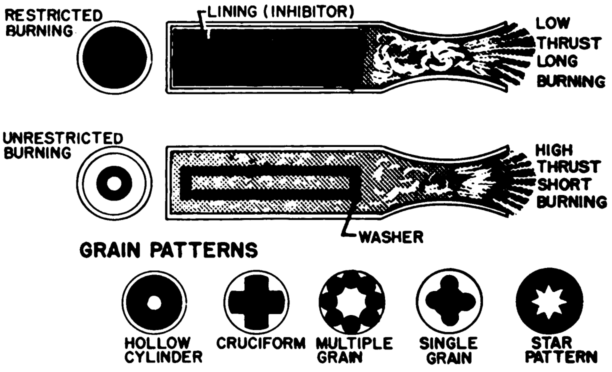
Jet motors used in guided missiles depend on heat energy for the force necessary to accelerate the ejected matter, and are called THERMAL JETS ("thermal" means "heat"). The heat energy is supplied by a chemical reaction, usually an oxidation process. In order for this oxidation process to occur, two substances are required—a fuel and an oxidizer, a substance having a large oxygen content.

Thermal jets are classified by the manner in which the oxygen is acquired. The two main classes are: ROCKETS, which carry their own oxidizer as well as fuel; and ATMOSPHERIC JETS, which utilize the oxygen in the atmosphere. The rocket operates independently of its surroundings, while the atmospheric jet is an airbreathing motor, and is limited to operation within the earth's atmosphere.

ROCKETS consist of three major parts—propellant, combustion chamber, and nozzle. The propellant is the combination of fuel and oxidizer necessary for the chemical reaction which generates the gases that are accelerated to high velocity and pass through the exhaust nozzle. Rockets are classified according to the state of the propellant used—solid or liquid.

The solid-propellant rocket is noted for its simplicity and is used in most missiles lanuched from ships. Polaris, Tartar, Terrier, and Talos are the outstanding examples of missiles using solid propellants for propulsion. The liquid propellant rocket is much more complicated than the solid-propellant. Because it can be cooled effectively and since the flow of propellant can be controlled by valves, the liquid-propellant rocket can operate for longer periods of time, and is applicable to long-range missiles.

There are two main types of solid-propellant rockets—RESTRICTED BURNING and UNRESTRICTED BURNING, shown in figure 3-5. In the restricted-burning rocket, the propellant is allowed to burn on only one surface at a time. An example of restricted burning is the manner in which a cigarett burns. In the unrestricted-burning rocket the propellant is allowed to burn on several surfaces at once. As a result, relatively high thrust is produced, but it lasts for only a short period of time as indicated in figure 3-5. The different amounts of thrust are obtained by the use of different patterns of propellant grains, some of which are shown in the figure.



12.26

Figure 3-5.—Types of solid-propellant rockets.

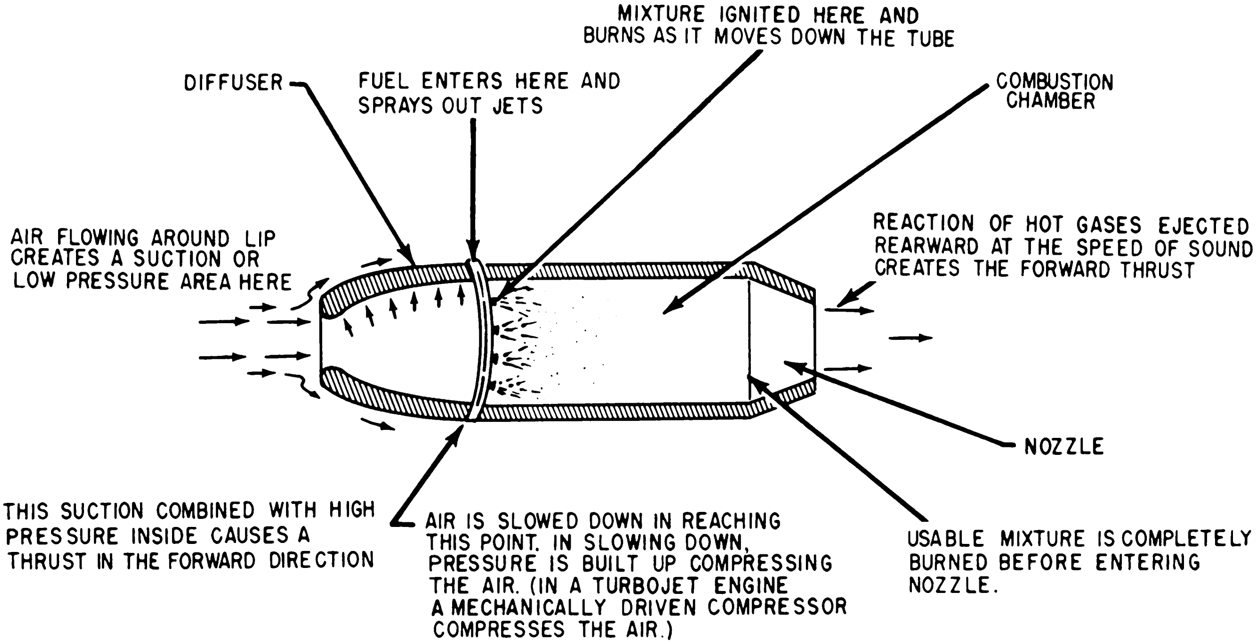
In the case of both the restricted- and unrestricted-burning solid propellants, it is essential that no detonation of the propellant takes place because all of the propellant is stored in the combustion chamber. It should be clearly understood that the propellant burns at a definite and controlled rate—it does not explode. To start the combustion process, some form of electrically detonated squib is ordinarily used to ignite a smokeless or black powder charge, which, in turn ignites the propellant.

Because rockets carry both fuel and oxidizer, the SPECIFIC FUEL CONSUMPTION—the pounds of propellant consumed per hour per pound of thrust—is much higher than that of other thermal jets. The thrust developed is essentially constant and is independent of the speed of the rocket.

ATMOSPHERIC JETS. Atmospheric jets take air from the atmosphere, increase its pressure, and feed it into the combustion chamber where it is combined with the fuel. There are two basic methods of increasing the pressure of the incoming air—by using a mechanical compressor, or by utilizing the action of a diffuser (a duct of varying cross section designed to convert high-speed airflow into low-speed flow at increased pressure). The three types of atmospheric jets are: TURBOJETS, PULSE jets, and RAMJETS. We are interested in the ramjet.

The RAMJET, which is sometimes called the FLYING STOVEPIPE or ATHODYD, is a compressorless type of thermal jet, as shown in figure 3-6. The combustion process in the ramjet is continuous, and utilizes the action of the diffuser to create a "pressure barrier" which prevents the gases from escaping in the forward direction. In order for this diffuser action to occur, the ramjet must be boosted to a suitable speed, and consequently it cannot produce static thrust.

Ramjets are classified according to operating speed—subsonic and supersonic. Both classes operate in the manner shown in the figure; the basic difference is in the diffuser design. The ramjet has a higher specific fuel consumption than the turbojet, but at supersonic speeds the ratio of engine weight to developed horsepower is far superior to that of any other atmospheric jet. Ramjets are limited in range only by the amount of fuel they can carry, and can operate up to an altitude of about 90,000 feet.


MIXTURE IGNITED HERE AND BURNS AS IT MOVES DOWN THE TUBE
DIFFUSER
FUEL ENTERS HERE AND SPRAYS OUT JETS
COMBUSTION CHAMBER
AIR FLOWING AROUND LIP CREATES A SUCTION OR LOW PRESSURE AREA HERE
REACTION OF HOT GASES EJECTED REARWARD AT THE SPEED OF SOUND CREATES THE FORWARD THRUST
NOZZLE
THIS SUCTION COMBINED WITH HIGH PRESSURE INSIDE CAUSES A THRUST IN THE FORWARD DIRECTION
AIR IS SLOWED DOWN IN REACHING THIS POINT. IN SLOWING DOWN, PRESSURE IS BUILT UP COMPRESSING THE AIR. (IN A TURBOJET ENGINE A MECHANICALLY DRIVEN COMPRESSOR COMPRESSES THE AIR.)
USABLE MIXTURE IS COMPLETELY BURNED BEFORE ENTERING NOZZLE.

12.30

Figure 3-6.—Operating cycle of the ramjets.

MISSILE AERODYNAMICS

Guided missiles travel through and are affected by the earth's atmosphere. The atmosphere is the gaseous envelope surrounding the earth to a height of roughly 250 miles. One of the most important characteristics of the atmosphere is the change in air density with a change in altitude. (Density is a measure of the weight per unit volume of a substance.) Because of the significant decrease in air density with altitude, a missile flying at 35,000 feet encounters less air resistance to its passage—that is, less DRAG—than does a missile flying close to sea level.

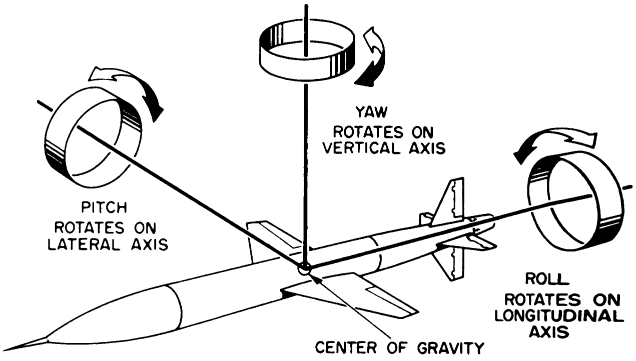
BASIC FLIGHT PRINCIPLES

Aerodynamics is the science that deals with the motion of air and other gases, and with the forces acting on bodies moving through these gases. The principles of aerodynamics which underlie the operation of most aircraft also apply to missiles, at least in some phases of flight. Before discussing high-speed missile flight, let us consider the motions and forces that are common to both guided missiles and airplanes.

Basic Motions

Like any moving body, the guided missile executes two basic kinds of motions: ROTATION and TRANSLATION. In pure rotation all parts of the body pivot about the center of gravity, describing concentric circles around it. In movements of translation, or linear motions, the center of gravity of the body moves along a line, and all the separate parts follow lines parallel to the path of the center of gravity. Any possible motion of the body is composed of one or the other of these motions, or is a combination of the two.

Missiles, like other aircraft, are free to move in three dimensions. To describe their motions we use a reference system containing three reference lines, or axes. The missile axes, illustrated in figure 3-7, are three mutually perpendicular lines which intersect at the center of gravity of the missile.



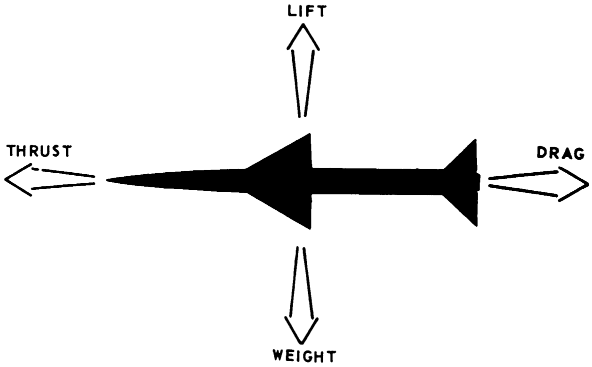
33.22
Figure 3-7.—Missile axes.

Three kinds of rotary movements can be made by the missile: PITCH, ROLL, and YAW. Pitch, or turning up or down, is rotation about the lateral axis, the reference line in the horizontal plane, perpendicular to the line of flight. The missile rolls, or twists, about the longitudinal axis, the reference line running through the nose and tail. It yaws, or turns to the right or left, about the vertical axis. Rotary motions about all three of these axes are controlled by devices within the missile. Hereafter, these axes will be referred to as the pitch axis, the roll axis, and the yaw axis.

Aerodynamic Forces

The principal forces acting on a missile in level flight are THRUST, DRAG, WEIGHT, and LIFT. Like any force, each of these is a vector quantity which has magnitude (length) and direction. These forces are illustrated in figure 3-8.

Thrust is directed along the longitudinal axis of the missile and is the force which propels it forward at speeds sufficient to sustain flight. Drag is the resistance offered by the air to the passage of the missile body through it, and is directed rearward. The weight of the missile is the force of gravity on



33.23
Figure 3-8.—Forces acting on a moving missile.

the body, and is directed downward toward the center of the earth. Opposed to the force of gravity is the lift, an upward force which supports the body. Lift is directed perpendicular to the direction of drag.

Lift is produced by means of pressure differences. The primary factor contributing to lift is that the air pressure on the upper surface of an airfoil (wing) must be less than the pressure on the underside. The amount of lifting force provided is dependent to a large extent on the shape of the wing. Additional factors which determine the amount of lift are the wing area, the angle at which the wing surface is inclined to the airstream, and the density and speed of the air passing around it. The airfoil that gives the greatest lift with the least drag in subsonic flight has a shape similar to the one illustrated in figure 3-9.

Some of the standard terms applied to airfoils are included in the sketch (fig. 3-9). The foremost edge of the wing is called the LEADING EDGE, and that at the rear the TRAILING EDGE (fig. 3-9A). A straight line between the leading and trailing edges is called the CHORD. The large arrow (fig. 3-9B) indicates the RELATIVE WIND, the direction of the airflow with reference to the moving airfoil. The ANGLE OF ATTACK is the angle between the chord and the direction of the relative wind.

The relative wind strikes the tilted surface, and as the air flows around the wing different amounts of lifting force are exerted on various points on the airfoil. The sum (resultant) of all these forces is equivalent to a single force acting at a single point and in a particular direction. This point is called the CENTER OF PRESSURE. From it lift can be considered to be directed perpendicular to the direction of the relative wind.

The dynamic or impact force of the wind against the lower surface of the airfoil contributes to lift but the major portion of the lifting force is obtained from the differential pressure of the air above and below the airfoil. The angle of attack causes the air flowing over the wing to travel a greater distance than the air which flows under the wing. The air flowing over the wing will increase its speed, and thus cause a reduction in air pressure above the wing. The greater the distance the air must travel, the faster it will travel and the lower its pressure will become. The air pressure is therefore higher under the wing and the pressure difference is a force acting on the wing in the direction of the lower pressure. The magnitude of the lifting force is proportional to the pressure difference.

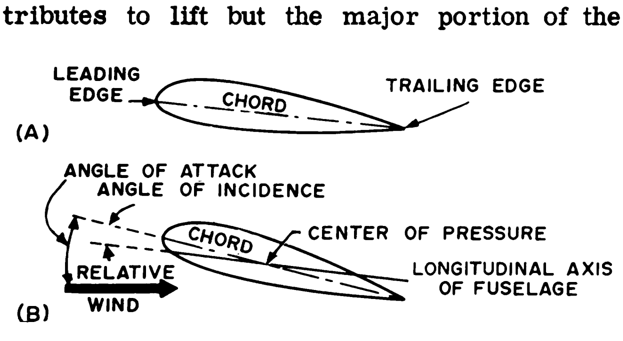


Figure 3-9.—Wing cross section. 33.24

ACCELERATION

Acceleration is a change in either speed or direction of motion. Thus, a missile accelerates as it increases or decreases speed along the line of flight, or if it changes direction in turns, dives, or pullouts, or as a result of a gust of wind. During accelerations a missile is subjected to large forces which tend to keep it flying along its original line of flight. This is in accordance with Newton's first law of motion which states: A body remains at rest or in a state of uniform motion in a straight line unless acted upon by an external force.

The force which acts on the missile during acceleration is measured in terms of the standard unit of gravity, abbreviated by the letter "g." A freely falling body is attracted to the earth by a force equal to its weight with the result that it accelerates at a constant rate of approximately 32 feet per second per second. Its acceleration while in free fall is said to be one "g." Missiles making rapid turns or responding to large changes in thrust will experience accelerations many times that of gravity, the ratio being expressed as a number of "g's." The number of "g's" which a missile can withstand is one of the factors which determines its maximum turning rate and the type of launcher suitable for the weapon.

MACH NUMBERS AND SPEED REGIONS

Missile speeds are expressed in terms of MACH NUMBERS rather than in miles per hour or knots. The Mach number is the ratio of missile speed to the local speed of sound. For example, if a missile is flying at a speed equal to one-half the local speed of sound, it is said to be flying at Mach 0.5. If it moves at twice the local speed of sound, its speed is then Mach 2. (The term "Mach number" is derived from the name of an Austrian physicist, Ernst Mach, who was a pioneer in the field of aerodynamics.)

Local Speed of Sound

The speed expressed by the Mach number is not a fixed or constant quantity since the speed of sound in air varies directly with the square root of the absolute temperature of the air. For example, it decreases from 760 miles per hour (mph) at sea level (for an average day when the air is 59° F) to 661 mph at the top of the troposphere. The speed of sound remains constant (with the temperature) between 35,000 feet and 105,000 feet, then rises to 838 mph, reverses, and falls to 693 mph at the top of the stratosphere. Thus you can see that the speed of sound will vary with locality.

The range of aircraft and missile speed is divided into four regions which are defined with respect to the local speed of sound. These regions are as follows.

SUBSONIC FLIGHT, in which the airflow over all missile surfaces is less than the speed of sound. The subsonic division starts at Mach 0 and extends to about Mach 0.75. (The upper limit varies with different aircraft, depending on the design of the airfoils.)

TRANSONIC FLIGHT, in which the airflow over the surfaces is mixed, being less than sonic speed in some areas and greater than sonic speed in others. The limits of this region are not sharply defined but are approximately Mach 0.75 to Mach 1.2.

SUPERSONIC FLIGHT, in which the airflow over all surfaces is at speeds greater than sound velocity. This region extends from about Mach 1.2 upward.

HYPERSONIC FLIGHT, in which the time of passage of the missile is of the order of RELAXATION TIME. Relaxation time is the time required for molecules of air to adjust themselves to the presence of a body or to readjust themselves after the passage of the body. Mach numbers on the order of 10 may be considered as hypersonic. Velocities that are not hypersonic at sea level may become so at high altitudes, since relaxation times will be longer where densities are relatively low.

Subsonic Flight

At subsonic speeds, sustained flight is dependent on forces produced by the motion of the aerodynamic surfaces through the air. If the surfaces of airfoils are well designed, the stream of air flowing over, under, and around them are smooth, conforming to the shapes of the airfoils. If, in addition, the airfoils are set to the proper angle and if motion is fast enough, the airflow will support the weight of the aircraft or missile.

Transonic and Supersonic Flight

Control of missiles in the transonic and supersonic regions differs somewhat from that at subsonic speeds. Particularly in the transonic regions are the effects varied, depending mainly on the characteristics of the missile involved. The differences in control may be the result of COMPRESSIBILITY, a property of the airstream which is not prominent at low speed but which cannot be ignored at high speeds.

THE NATURE OF COMPRESSIBILITY.—When an object moves through the air, it continuously produces small pressure disturbances in the airstream as it collides with the air particles in its path. Each such disturbance—a small variation in the pressure of the air—is transmitted outward in the form of a weak pressure wave. Each expanding pressure wave travels at the speed of sound. Although each pressure wave expands equally in all directions, the important direction is that in which the object generating it is moving.

As long as the missile is moving at low subsonic speeds the pressure waves, traveling at the speed of sound, move out and away from the missile. Therefore, when the missile arrives at any given point, the air particles agitated by the pressure wave are already in motion and can easily and smoothly flow around it. But, when the missile approaches the speed of sound, the pressure waves are generated almost as fast as they can move away from the missile. This means that the greater the speed of the missile, the fewer the number of air particles that will be able to move from its path, with the result that the air begins to pile up in front of the missile. In other words, more air is compressed in the area just ahead of the missile.

When the missile reaches the speed of sound, it is moving at the same speed as the pressure waves it generates. Thus a situation occurs in which the air particles forward of the compressed region at one moment are completely undisturbed, and at the next moment are compelled to undergo drastic changes in velocity, density, temperature, and pressure. Because of the sudden nature of the transition, the boundary between the undisturbed air and the compressed region is called a SHOCK WAVE.

TYPES OF SHOCK WAVES.—There are several types of shock waves, the principal classes being the NORMAL and the OBLIQUE. These differ primarily in the way in which the airstream passes through them. In the normal (or perpendicular) wave, the air passes through without changing direction, and the wavefront is perpendicular to the line of flow. The normal shock wave is usually very strong; that is, the changes in pressure, density, and temperature within it are great. The air passing through the normal shock wave always changes from supersonic to subsonic velocity.

Oblique shock waves are those in which the airstream changes in direction upon passing through the transition marked by the wavefront. These waves are produced in supersonic airstreams at the point entry of wedgeshaped and other sharply pointed bodies. The resulting wavefronts make angles of less than 90° with the line of flight. Like the normal shock wave, the oblique wave occurs at a point of change in velocity from a higher to a lower value. The change in speed is usually from supersonic to subsonic but not always so. In some cases the airflow is supersonic both upstream and downstream of the oblique wave. In general, the variations in density, pressure, and temperature are less severe in the oblique wave than in the normal shock wave.

Stability and Lift in Modern Missiles

So far we have discussed the principles of producing lift by the use of cambered wings (curved wing). Cambered wings are still used on conventional aircraft but are not used on most present day guided missiles. Most operational missiles use streamlined fins to provide stability and some lift.

The Navy's surface-to-air missiles (RIM), are designed to travel at supersonic speeds. Lift is achieved almost entirely by the thrust of the main propulsion system. The missile fins must present streamlined airflow surfaces to reduce air turbulence, and therefore are not cambered like the conventional wing. The lift that a fin does contribute is based on a slightly different principle. At subsonic speeds a positive angle of attack will result in impact pressure on the lower fin surface which will produce lift just as with the conventional wing. At supersonic speeds, the formation of EXPANSION WAVES and oblique shock waves also contributes to lift. Figure 3-10 shows the upper surface of a supersonic fin. Due to the fin shape, the air is speeded up through a series of expansion waves. This results in a low pressure area above the fin. Figure 3-11 shows the fin cross section. Beneath the fin, the force of the airstream (dynamic pressure) and the formation of oblique shock waves result in a high pressure area. The differences in pressure above and below the fin produce lift.

The flight of an arrow is an example of the stability provided by fixed fins. The feathered fins on an arrow present streamlined airflow surfaces which ensure accurate flight. As long as the arrow is flying true its fins present their slim longitudinal axes to the airflow. If the arrow attempts to tumble or to curve left or right, it must do so against the resistance of the lateral axis of the fins to the airflow. The lateral axis of the fin has a large area that provides a proportionally large amount of resistance to any deviation from normal flight.

You should realize that fins use air and air pressures to provide both lift and stability. Thus fins cannot control a missile outside the earth's atmosphere. The Polaris missile, for example, has no fins; its lift is achieved entirely by the thrust of the main propulsion system.

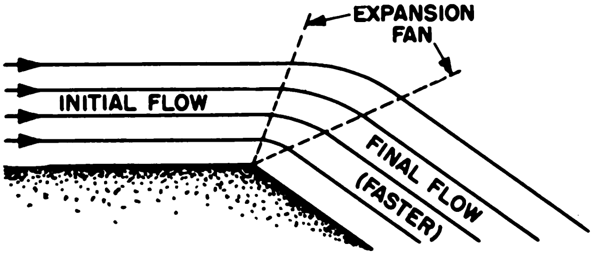


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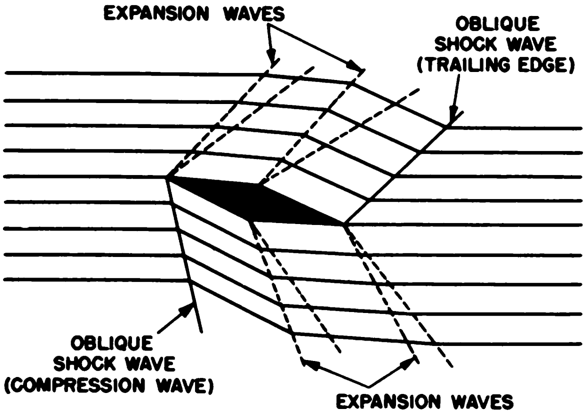
Figure 3-10. —Expansion wave.


EXPANSION WAVES
OBLIQUE SHOCK WAVE (TRAILING EDGE)
OBLIQUE SHOCK WAVE (COMPRESSION WAVE)
EXPANSION WAVES

33.30
Figure 3-11.—Airflow about supersonic fin.

CONTROL SURFACES

Movable fins, called control surfaces, provide a means for controlling missile attitude. A control surface provides control by presenting an obstacle to airflow. This causes a force (due to impact pressure) to be exerted on the surface. The magnitude of the force depends on the angle between the control surface and the direction of airflow. Figure 3-12 shows the effects of control surface movement.

Fixed (stabilization) fins and movable control surfaces may be located in several ways on the missile. Figure 3-13 A and B shows two possible combinations. In the first, control is achieved by movement of the after surfaces. In the second, control is achieved by movement of forward and after surfaces. Other combinations are possible and are used in some operational missiles. The important thing for you to remember is that control is attained due to impact pressure exerted on the control surfaces and that fixed fins contribute primarily to stability.

Fin Designs

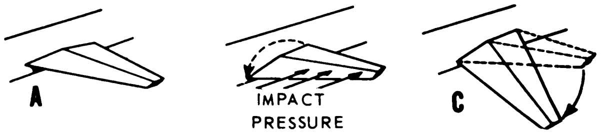
Supersonic fins are symmetrical in thickness cross section and have a small thickness ratio—the ratio of the maximum thickness to the chord length. The DOUBLE WEDGE, shown in figure 3-14, has the least drag for a given thickness ratio, but in certain applications it is inferior because it lacks strength. The MODIFIED DOUBLE WEDGE has a relatively low drag (although its drag is usually higher than a double wedge of the same thickness ratio) and is stronger than the double wedge. The BICONVEX, also shown in the figure, has one and one-third greater drag than a double wedge of the same thickness ratio. It is the strongest of the three but is difficult to manufacture.

The planform of the fins—the outline when viewed from above—is usually either the DELTA-MODIFIED DELTA (raked tip) or RECTANGULAR type (fig. 3-15). These shapes considerably reduce unwanted shock wave effects.

ARRANGEMENT OF FINS.—Fins are mounted on the airframe in several arrangements, some of which are shown in figure 3-16. The CRUCIFORM is the most popular tail arrangement. It is used in surface-to-air missiles. Both the INLINE and INTERDIGITAL cruciform are widely used, especially for supersonic missiles.

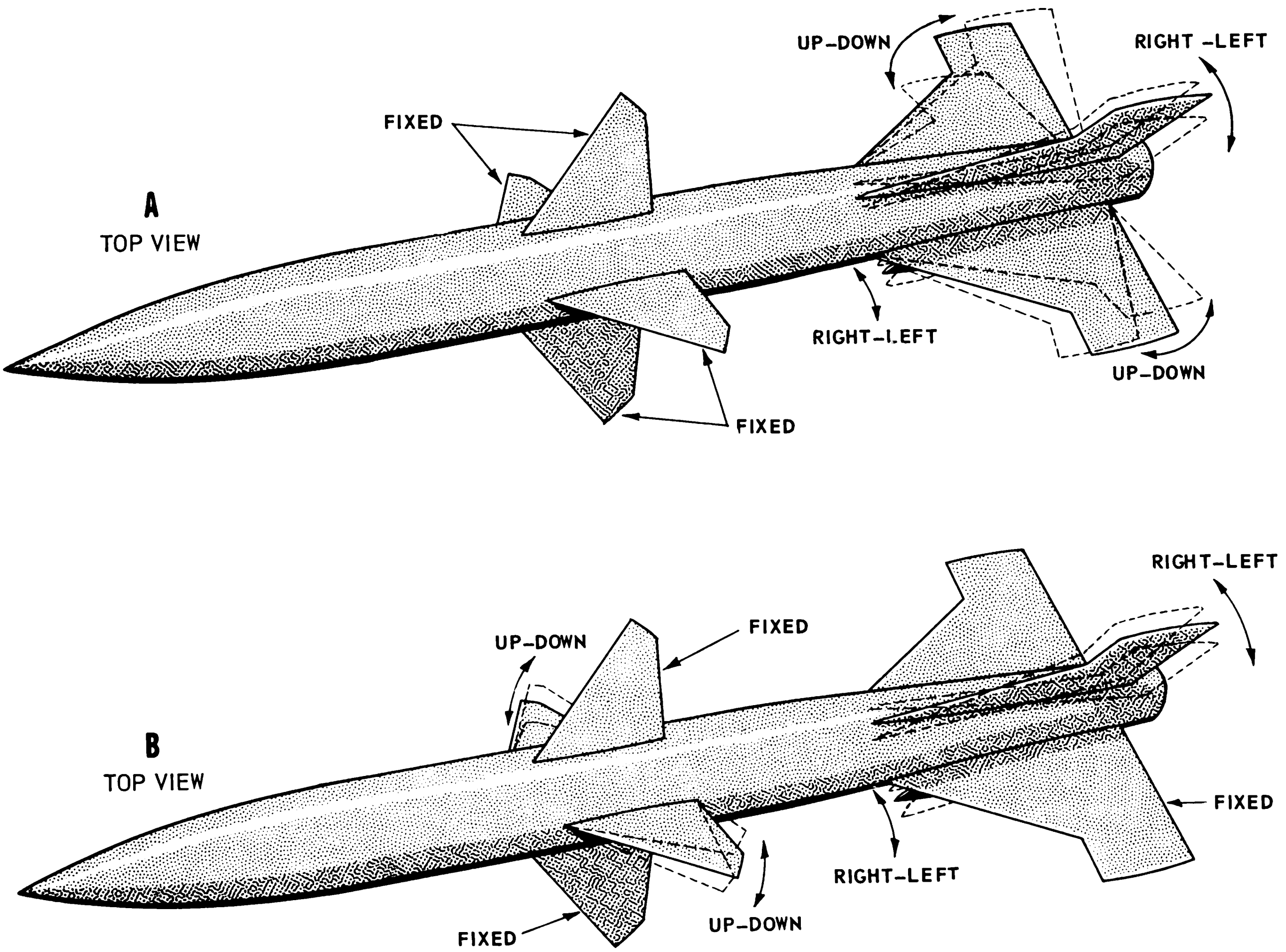
CONTROL SYSTEM

The control system operates the guided missile's control surfaces (wings and fins) to bring the missile to the desired course and to keep it on course. The control system therefore must know the desired flight path of the missile and its position and attitude with respect to the path. The missile's guidance system supplies the control system with signals which represent the desired path. Devices in the control system measure the missile's attitude in its three axes of motion (roll, pitch, and yaw) with respect to the path. Hence the guidance and control systems work together to guide the missile. We will consider the overall operation of a missile's guidance and control system before we discuss the subsystems. Incidentally, in some guided missiles the guidance and control system is called the STEERING SYSTEM. This will not hinder our discussion since we will consider a basic missile guidance system.



A. CONTROL SURFACE IN NEUTRAL POSITION
B. CONTROL SURFACE TILTED
C. MISSILE ROLLS DUE TO IMPACT PRESSURE

33.31
Figure 3-12.—Effect of moving control surfaces.



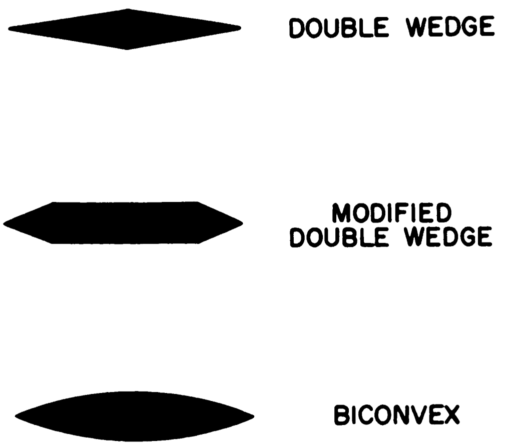
33.32

Figure 3-13.—Location of fins and movable control surfaces.

In figure 3-17 we show that the complete system for steering and stabilizing a surface-to-air missile may be considered as consisting of two major divisions or systems: (1) the guidance system and (2) the control system, which functions similarly to an automatic pilot in an aircraft. For convenience, we will include the gyros and the control surfaces (wings and fins) as part of the control system.

In many ways a guidance and control system is simply a flying servomechanism. At first thought this idea may not be clear to you. So to make it clearer, let's review the definition of a servomechanism and see if the definition fits a missile guidance and control system. You learned in Basic Electricity, NavPers 10086-A, that, and we quote the text—"A servomechanism is an electromechanical device that positions an object in accordance with a variable signal. The signal source may be capable of supplying only a small amount of power. A servomechanism operates to reduce the difference (error) between two quantities."

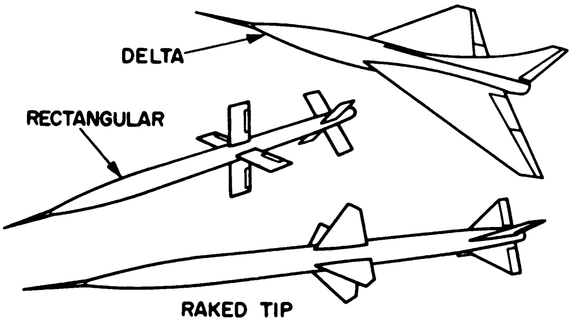
A guidance and control system meets the requirements of a servomechanism as it is implied in the above definition. The guidance portion of the system develops the variable input signal. The input signal represents the desired course to the target. The missile control system operates to bring the missile onto the desired course. Therefore, you can say that the output of the guidance and control system is the actual missile flight path. If there is a difference between the desired flight path (input) and the one the missile is actually on (output), then the control system operates to



33.33
Figure 3-14.—Supersonic fin cross sections.

change the position of the missile in space to reduce the error. When the missile has been steered to the desired course, the guidance system will detect no error and the control system will not move the control surfaces in response to a guidance error, because there isn't any.

The units of the guidance system may be carried in the missile, or they may be distributed between the missile and the launching ship. The principal function of the guidance system is to detect the presence of the target and track it; to determine the desired course to the target; and to produce electrical steering signals which indicate the position of the missile with respect to the required course.



33.34
Figure 3-15.—Fin planforms.

The units that respond to the guidance signals and actuate the control surfaces make up the major division referred to in figure 3-17 as the CONTROL SYSTEM. The units in the control system may be considered as consisting of two groups: the COMPUTER, and the CONTROL-SURFACE SERVOSYSTEM.

Specific computer units vary widely in design because of basic differences in the type of guidance used. But in most cases this section

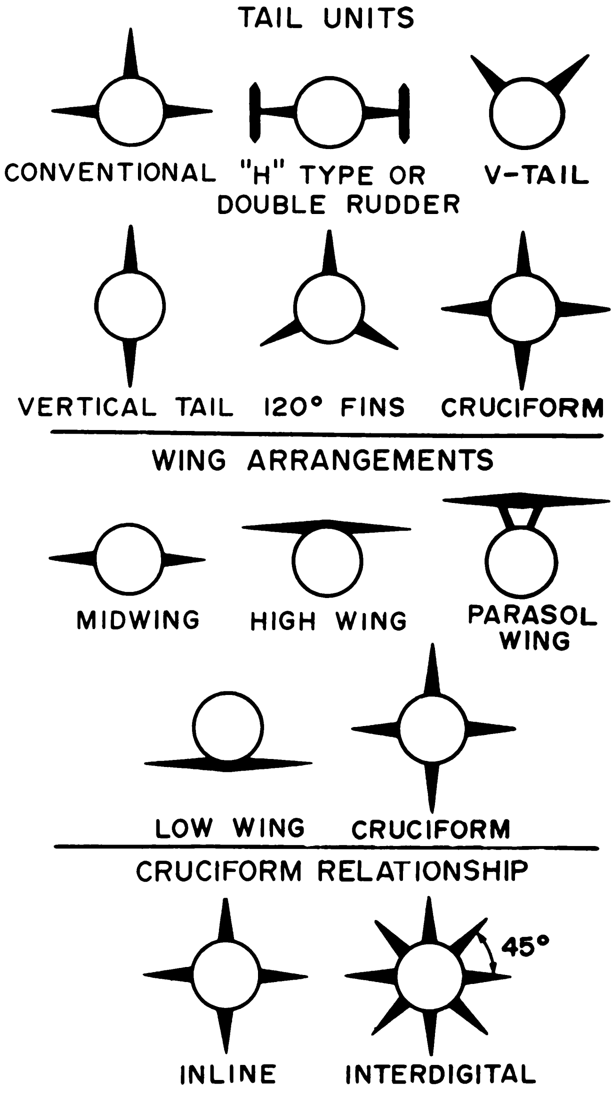


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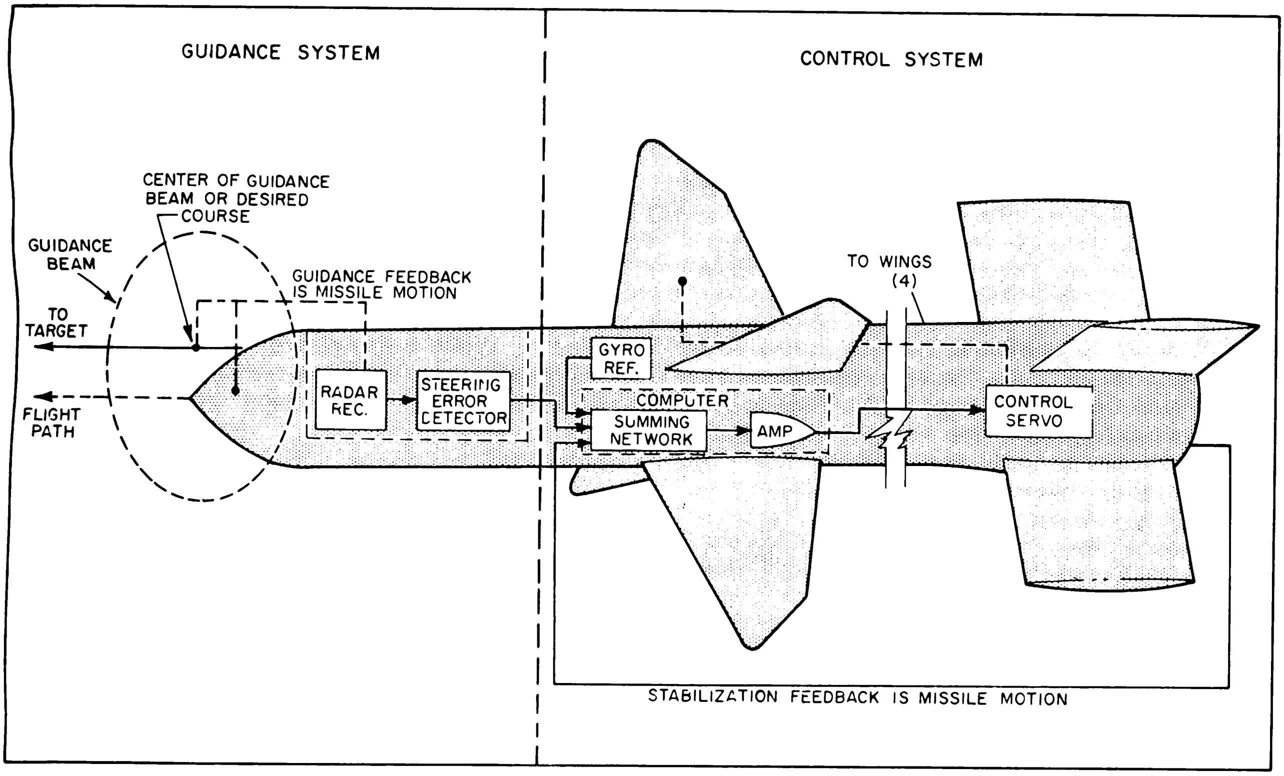
Figure 3-16.—Arrangement of fins.



83.17

Figure 3-17.—Essential parts of a basic missile guidance system.

contains damping instruments (accelerometers and rate gyros), summing networks (electrical circuits that add and subtract voltages), and servoamplifiers as principal components. In general these units originate information about missile motion and flight attitude, add this data to incoming guidance signals, and produce output voltages suitable for operating the control-surface servo.

A typical control-surface servosection is made up of hydraulic units. This section serves as a power stage of the control system; it releases large amounts of energy under accurate control. The principal parts of this section are electrically operated servovalves and the wing or tail hydraulic actuator units which make the adjustments to guide and stabilize the missile.

Types of Feedback Loops

As indicated by the feedback loops shown in figure 3-17, the basic operation of the guidance and control system is based on the closed-loop or servo principle. The control units make corrective adjustments of the missile control surfaces when a guidance error is present, or, in other words, when the missile is not on the correct course to the target. The control units will also adjust the control surfaces to stabilize the missile in roll, pitch, and yaw. You must keep in mind that guidance and stabilization are two separate processes, even though they occur simultaneously. To make this idea clearer, think of yourself throwing a dart with its tails removed. It is possible for you to hit the bulls-eye of a target because your arm and brain guide the dart onto the proper trajectory to score a hit. But without its tail surfaces to stabilize it, it is very possible that the dart will land on the target in some position (attitude) other than point first. Well, missiles are like darts or arrows in this respect, and must be stabilized about the roll, pitch, and yaw axes so that the missile will fly nose first and will not oscillate about its direction of flight. In summary we can say that if there is an error in missile heading due to guidance or stabilization, the corrective actions taken by the control system are such that any error present in the system is reduced to zero. This is true servo-action, as you have learned in previous Navy courses on basic electricity and electronics.

Now that you have a general picture of the overall operation of a missile guidance and control system, let's turn our attention to the feedback loops in our flying servo.

Guidance Feedback Loop

The guidance feedback loop is indicated by the broken line between the desired course line and missile flight path (fig. 3-17). The loop is not a physical circuit, but rather a method of operation that is built into the system. By means of this operation, the position of the airframe, as well as the guidance signals, determines the amplitudes and polarities of the guidance signals that actuate the control units.

For example, in the beam-rider system, steering (guidance) error voltages are produced in the radar receiver in the guidance section by comparing the position of the missile with the center of the guidance beam. If the missile is not flying along the beam axis, then the guidance system produces error voltages and sends them to the control section. The control section makes corrective adjustments of the control surfaces in response to the error signals. As the missile approaches the center of the radar beam (which defines the course to the target), the error voltages get smaller, and become zero when the missile flies along the beam axis.

In the operation of most homing missiles, error signals are produced by measuring the position of the target with respect to the line of sight of a gyro stabilized radar antenna called the seeker head. It is located in the nose of the missile and points at the target. A line drawn through the fore-and-aft axis of the antenna to the target describes the desired course for the missile. Any deviations of the missile that throw the antenna off course result in guidance signals which are sent to the control system. The control system reacts by correcting the missile heading, and the error signals progressively decrease and approach zero as the missile comes on course. Thus, in either beam riding or homing systems, feedback action is a fundamental process of guidance, and consists of altering the position of the airframe. Thus the missile acts like a position servo as it responds to guidance signals.

Stabilization Feedback Loop

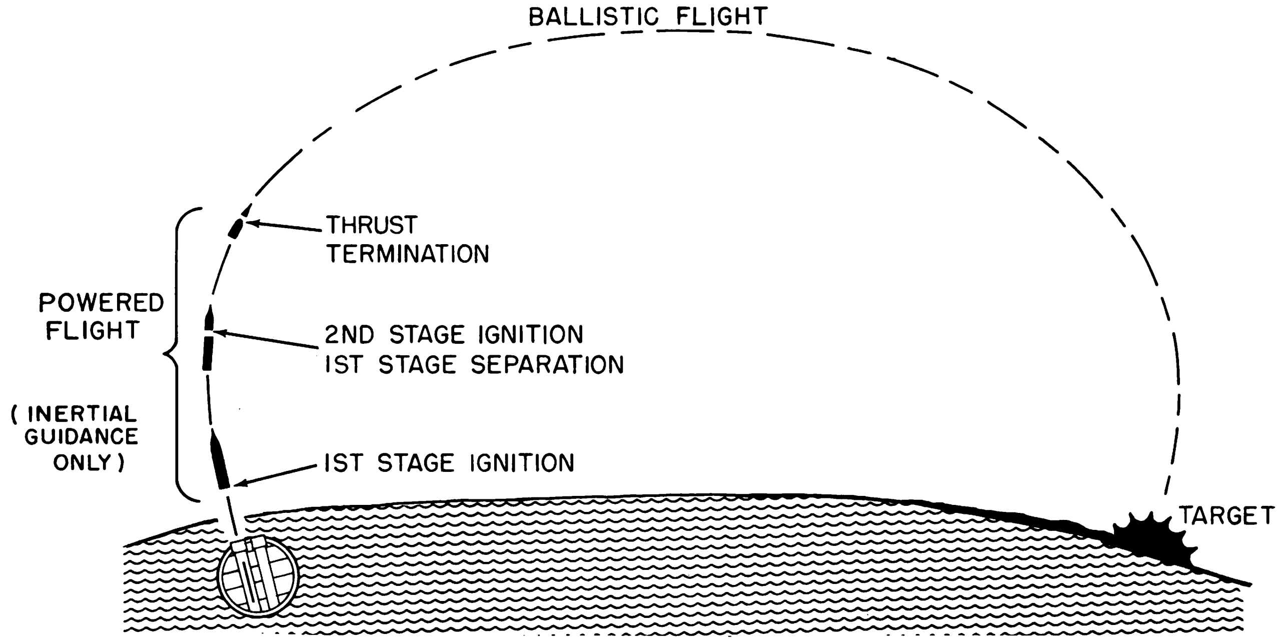
The stabilization feedback loop shown in figure 3-17 indicates in a general way the basic method used in most missile control systems for stabilizing the missile. The stabilization loop is completed by the inputs and outputs of DAMPING devices, which in most systems are rate gyros and accelerometers. The input to each of these instruments is some motion of the missile. The rate gyros measure angular velocity about a missile axis and the accelerometers measure the linear acceleration *along* an axis. Thus the control system receives stabilization signals that are proportional to the particular component of motion to which a damping instrument is sensitive.

The damping voltages are applied to the input of the summing circuits in the computer. Another input to the summing network is the guidance signals. The two sets of signals are added in the summing network and produce control signals which ultimately keep the missile on course and in the proper flight attitude.

MISSILE GUIDANCE PHASES

Missile guidance is generally divided into three phases—boost, midcourse, and terminal. A missile is boosted to flight speed as rapidly as possible. The boost period lasts from launch until the booster burns up its fuel. If the missile has a separate booster, it will drop away from the missile at burnout. The missile's flight path during boost extends from the launcher to a point in space, and at the end of its boost period the missile should be at this point. If the missile is a homing missile, it must "look" in a predetermined direction for the target. The fire control computer calculates the predicted target position based on where the missile should be at the end of its boost phase. This information is fed into the missile before it is launched. If the missile is a beam rider, it must be in a position where it can be captured by a radar guidance beam. Obviously, a missile must fly along its prescribed boost flight path for the correct period of time and at the proper average velocity.

The MIDCOURSE phase begins where the boost phase ends, and ends where the terminal or last phase begins. It is during the midcourse phase that most of the corrections to the missile's flight path are made.



33.269

Figure 3-18.—Polaris trajectory (not to scale).

The TERMINAL phase occurs as the missile approaches the target. This phase requires very high accuracy from the guidance system since the missile may have to make sharp turns and undergo high accelerations, especially against fast-moving and maneuvering targets.

GUIDANCE SYSTEMS

The guided missile can be controlled during its flight to reduce the effectiveness of enemy countermeasures, and to automatically adjust its flight path to compensate for changes in its environment. Guidance systems for the missiles we are concerned with can be divided into four groups: (1) self-contained, (2) command, (3) beam-rider, and (4) homing. In some missiles a single guidance system may be used for all three guidance phases, but most missiles have a different guidance system for each phase.

Self-Contained Guidance Systems

In a self-contained guidance system all the guidance and control equipment is inside the missile. The guidance system neither transmits nor receives signals during the missile's flight. This is a major advantage, since only limited countermeasures can be used against it. This means that the trajectory the missile must follow to hit the target must be calculated and fed into the missile before it is launched.

The inertial guidance system used in the Polaris missile is an example of a preset, self-contained guidance system. Polaris is a long-range surface-to-surface guided missile which can be launched from a submerged submarine.

Polaris uses inertial guidance during the first part of its flight. During the remainder of the flight, it is neither guided nor propelled; but follows a free ballistic trajectory, like a gun projectile. Figure 3-18 shows a typical flight path of a Polaris missile. If the submarine knows where it is and where the target is, a computer can determine the direction in which to aim the missile and the proper trajectory to hit the target. A statement of the preset guidance problem will be covered in the next chapter of this course; here we are interested in the equipment in the missile.

In setting up a flight plan for preset guidance, missile speed is used to determine the required time of flight. Assume, for example, that a missile is to be fired at a target 500 miles due north of the launching site. Also assume that the speed of the missile can be controlled, or at least can be predicted with enough accuracy to program the flight. If we assume an average missile speed of 2,000 miles per hour, the missle would require 15 minutes to travel from the launch site to the target. The preset information would cause the missile to achieve its cruising altitude, head north for 15 minutes, and then dive on the target.

It is important that you realize at this point that the actions carried out by a missile in flight may be preset to occur either after a certain amount of TIME has elapsed, or when a certain CONDITION has been achieved.

For example, a missile may be programmed to assume level flight 30 seconds after launch—or it may be programmed to assume level flight only after a specific altitude has been reached, this altitude being determined by an altimeter. As another example, missile booster separation may be scheduled to occur 6 seconds after launch—or it may be programmed to occur at the point that a certain thrust acceleration has been achieved. Course and speed changes as well as other functions can be carried out with relation to the elapse of specified time intervals or on the occurrence of other preset conditions.

The heart of the inertial guidance system is an arrangement of accelerometers that detect motions along their sensitive axes. To understand the function of the accelerometers in inertial guidance, let us first examine the principle of accelerometers in general terms.

ACCELEROMETERS.—An accelerometer is an inertia device. A simple illustration of the principle involved in accelerometer operation is the action of the human body in an automobile. You know that if an automobile is subjected to acceleration in a forward direction you are forced back in the seat. If the auto comes to a sudden stop, you are thrown forward. When the auto goes into a turn you tend to be forced away from the direction of the turn—that is, if the auto turns left, you are forced to the right, and vice versa.

In figure 3-19 we replace the human in an auto with a mass suspended in an elastic mounting system. Any accelerations of the auto will cause movements of the mass relative to the car. The amount of displacement will be proportional to the force causing the acceleration. The direction in which the mass moves in relation to the auto will be opposite to the direction of the acceleration.

The movement of the mass is in accordance with Newton's second law of motion which states that when a body is acted on by a force, its resulting acceleration is proportional to the force and inversely proportional to the mass of the body. In mathematical terms this may be expressed as $a = \frac{F}{M}$, or, by transposition, F = Ma, where F equals force, M equals mass, and a equals acceleration.

When the auto in figure 3-19 is standing still, the mass will be at its rest point. When the car starts off in the forward direction the mass will lag in proportion to the acceleration force. It will also tend to oscillate about its rest point due to the spring tension. If permitted to oscillate, the movement of the mass would not represent the true accelerations of the auto. To eliminate the unwanted oscillations, a DAMPER is included in the accelerometer unit. The damping effect should be just great enough to prevent any oscillations from occurring but still permit a significant displacement of the mass. When this condition exists, the movement of the mass will be exactly proportional to the accelerations of the auto.

APPLICATIONS IN MISSILES.—For an inertially guided missile to constantly determine

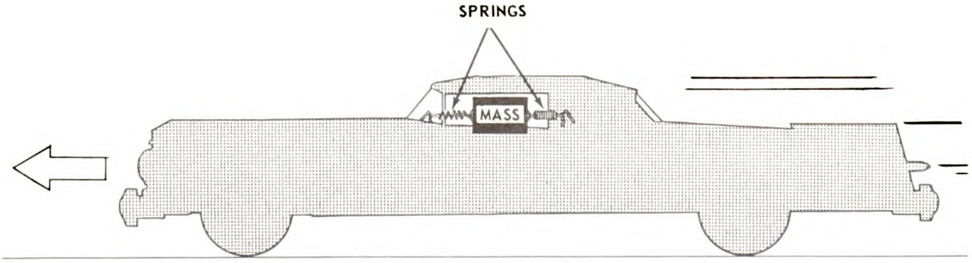


Figure 3-19.—Car with spring-suspended mass.

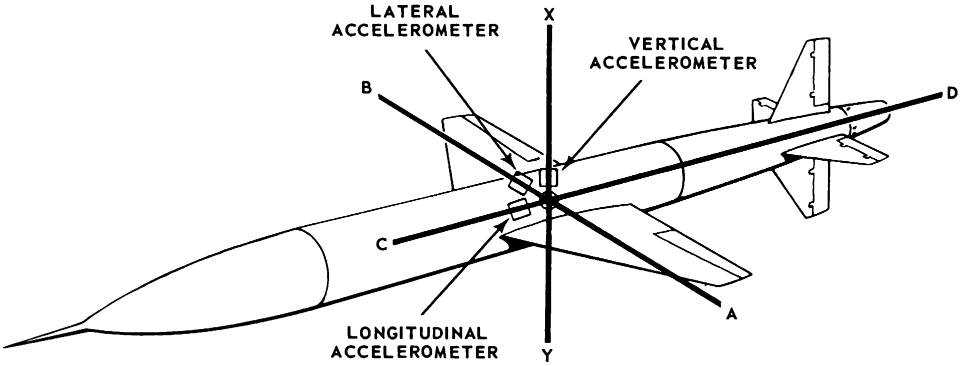


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Figure 3-20.—Accelerometers in guided missiles.

its position while in flight, all linear accelerations of the missile must be measured. To do this, three accelerometers are mounted in the missile as shown in figure 3-20. Any movement of the accelerometers with relation to the missile will be proportional to the outside forces acting on the missile, and therefore to the accelerations of the missile. Since these accelerometers are mounted on three mutually perpendicular axes, any accelerations of the missile along axis AB will be measured by movement of the lateral accelerometer. Any accelerations along axis CD will be measured by the longitudinally mounted accelerometer. Any accelerations along axis XY will be measured by the vertically mounted accelerometer.

If the missile is to determine its position at any point along its flight path, the accelerometers must be mounted in mutually perpendicular axes which continuously maintain their same relationships with some fixed reference point. To stabilize the accelerometers so that they will maintain these relationships throughout a long flight, gyroscopes are used. We will cover gyroscopes in a later chapter.

Assuming that we have stabilized the platform let us now see how a missile can determine its position and control its trajectory.

For the missile to keep track of its position, it must continuously determine its accelerations and velocity along the three stabilized accelerometer axes. Since acceleration is defined as

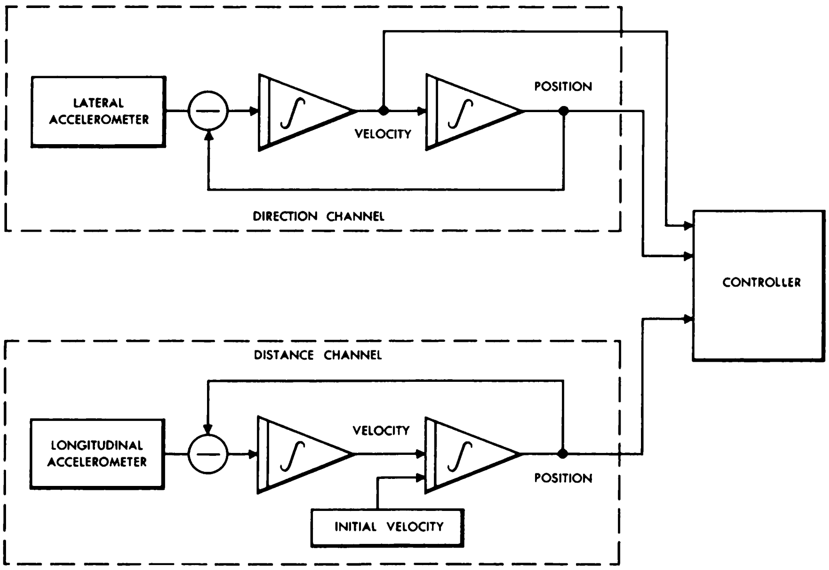

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Figure 3-21.—Simple inertial guidance system.

the rate of change of velocity, the process of INTEGRATION will yield missile velocity. Integration is, in effect, the process of adding up all of the INSTANTANEOUS values of a changing quantity.

Assume that a spring-suspended mass is mounted in a missile so that it will respond to the accelerations of the missile along its longitudinal axis. Also assume that the mass is connected to a potentiometer, in such a way that the potentiometer output is zero when the mass is at the neutral point. If the mass lags aft, the potentiometer output is a positive voltage; if the mass moves forward from the neutral point, the potentiometer output is a negative voltage. For an integrator, we can use a simple capacitor. During positive (forward) acceleration, the capacitor will gradually take on a positive charge from the potentiometer. If the acceleration then becomes zero, the charge on the capacitor will stop increasing, and will remain constant (indicating a constant velocity). If the acceleration becomes negative, the charge on the capacitor will begin to drain off (indicating a decreasing velocity). Thus the charge on the capacitor is the output of the first integrator.

If the first integrator output voltage is applied to the grid of a vacuum tube, it can be used to determine the rate at which current flows through the tube and into a second capacitor. The rate of current flow at any instant is proportional to the first integrator output, and therefore to missile velocity at that instant. Thus the charge on the second capacitor is the output of the second integrator, and represents the total distance traveled up to any given instant.

Figure 3-21 is a block diagram of a simple inertial guidance system. This system has two channels—one for lateral and one for longitudinal acceleration. It uses both the direction channel and the distance channel to determine missile position. Each channel contains an accelerometer and a circuit for double integration. The accelerometers detect missile velocity changes without the use of any reference outside the missile. The acceleration signals are fed to a computer which continuously produces an indication of both lateral and forward distance traveled by the missile. This is accomplished in each channel by integrating the missile acceleration signal to obtain a missile velocity signal. When this velocity signal is integrated, the result indicates the total distance that the missile has traveled.

DIRECTION CHANNEL.—If the missile is on course, the output of the direction channel will be zero at all times. If the missile drifts off course, the output voltage of the second integrator will show, by its amplitude and polarity, the distance and direction the missile is off course. The output of the first integrator in the direction channel is the direction rate signal. Both of the integrator voltages are used to determine the amount and direction of control required to bring the missile back on course.

DISTANCE CHANNEL.—The operation of the distance channel is much like that of the direction channel. The output magnitude of the first integrator indicates missile longitudinal velocity. The second integrator output voltage is proportional to the distance the missile has traveled. If the system does not start operating until after the launching phase is completed, the missile velocity at that time must be accounted for in the distance computation. A separate signal, representing initial velocity, must be fed to the input of the second integrator. It can then be combined with the output of the first integrator to indicate missile velocity at any given instant.

A comparison must be made between the distance the missile has traveled and the known distance between the launch point and the target. To do this, a voltage representing the distance to be traveled is set up as an initial condition just before missile launching. This preset voltage is combined, with opposite polarity, with the output of the second integrator. Thus the output of the distance channel decreases as the flight progresses. When the output falls to zero, the target or warhead release point ("dump point") has been reached.

A third channel for measuring missile altitude is usually included in the system. The principles of integration of the vertical accelerometer output are essentially the same as for distance and direction.

Attitude Control

Thus far we have considered the inertial system from the standpoint of determining and correcting missile position in a stabilized coordinate system. As mentioned earlier, this coordinate system is maintained by mounting the three accelerometers on three mutually perpendicular axes on the gyro-stabilized platform. Any linear deviations along the missile AXES OF TRANSLATION will be detected by accelerometer movement and corrected on the basis of the accelerometer outputs. In addition to correcting for deviations in position, we must also keep the missile at its proper attitude along the trajectory. By mounting pickoffs on the missile frame, any deviation in roll, pitch, or yaw will be detected with reference to the stable platform. The resulting attitude signals are related to the missile positional information generated by the accelerometers. We can therefore say that the correction signals generated by the computer network of the missile are composed of corrections along the axes of translation as detected by the accelerometers, and corrections about the axes of rotation as determined by missile angular movement with relation to the stabilized platform. These correction signals will then be applied to the controller in such a way as to keep the missile on its proper trajectory AND in the proper attitude throughout the flight.

Navy ballistic missiles are presently launched by submerged submarines. These FBM (Fleet Ballistic Missile) submarines determine their launching positions accurately by use of an inertial navigation system. The position of the target on the earth's surface is determined by reliable charts. The accelerometer axes of the missile are initially aligned with the local vertical and horizontal. After launch, the platform remains absolutely stable in space and can be said to be referenced to a fixed point in space. A precomputed ideal trajectory is preset into the missile. The preset information takes into account the movements of the target, the launching point, and the missile with respect to inertial space during the time of flight. The warhead release velocity which the missile must attain along its trajectory on the basis of a fixed time of flight is also preset. While in the power stage of flight, the missile continuously measures its linear accelerations on the basis of its inertial system and alters its trajectory to offset the outside forces causing unwanted accelerations. When the missile is on a proper trajectory and a correct velocity has been attained, the warhead is released and proceeds on toward the target with no further correction possible.

Beam-Rider and Command Guidance Systems

This group consists of the beam-rider systems, the command systems and modifications for each. These systems may be used for either midcourse or terminal guidance, depending on the range. They are used most effectively against air targets.

COMMAND GUIDANCE SYSTEMS.—A command guidance system is one in which directional commands are sent to the missile from some source outside it. The missile merely executes these commands. A simple command system is shown in figure 3-22. This system is used for controlling the drone targets employed in certain AA gunnery exercises.

In this system the operator visually observes the drone (tracking) and mentally decides the changes necessary in course, speed, and elevation (computing). Commands are then sent to the drone by radio (directing) where a receiver picks them up, and through the control system causes the drone to execute the desired maneuver (steering).

In a command system for surface-to-air missiles, two radars and a computer replace the human operator of the target-drone system.

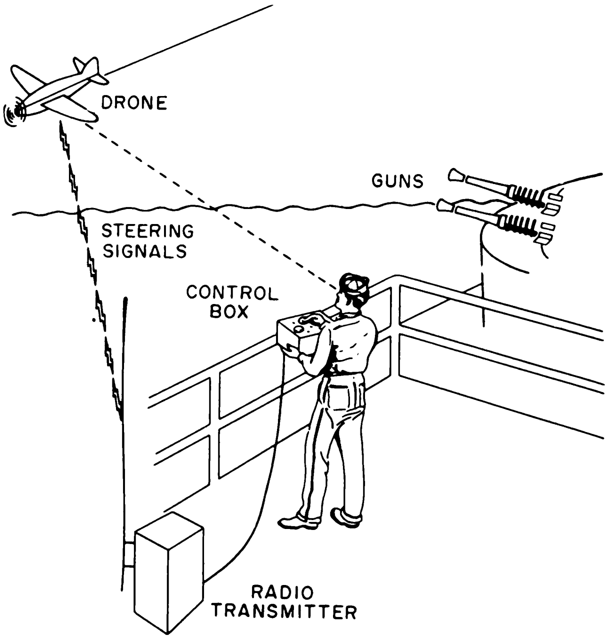

Figure 3-22.—Human command system for target drone. 12.31

One radar tracks the target and the other tracks the missile. The computer takes the two sets of tracking data and issues commands so that the missile will either collide with the target or pass within the lethal range of the warhead. The command signals may be sent to the missile by radio or by the missile tracking radar. The equipment in the missile is comparatively simple, consisting of a receiver and a control system. The shipboard equipment, however, is large and complex.

BEAM-RIDER GUIDANCE METHOD.—Beam-rider guidance is very similar to radar command guidance. In both systems, target information is collected and analyzed by suitable devices at the launching site or other control point—rather than by devices within the missile. In both systems, the missile makes use of guidance signals transmitted from the control point.

The principle difference between radar command guidance and beam-rider guidance is as follows: in the command system, guidance signals are specific commands, such as "turn right," or "turn left." But the control transmitter of a beam-rider guidance system transmits only information, not commands. By projecting a narrow beam of radar energy, the transmitter at the control station indicates the direction of the target (or, in some systems, the direction of a calculated point of intercept). The guidance equipment within the missile must interpret the information contained in the radar beam, and then formulate its own correction signals. Since these correction signals produce control surface movement which keep the missile in a certain relationship with the controlling beam, the missile is said to "ride" the beam to its target.

The beam-rider system is highly effective for use with short-range and medium-range surface-to-air missiles. For missiles of longer range, a beam-riding system may be used while the missile is still within effective range of the transmitting radar. As it approaches the limit of beam-riding range, the missile may switch over to some other form of guidance, usually homing guidance.

The basic principles of radar and the general characteristics of a radar beam are discussed in Basic Electronics, NavPers 10087-A. Before getting into the details of the beam-rider guidance system, it might be a good idea to take a closer look at the subject of radar in the basic text. We will cover fire control radars in a later chapter in this course.

ONE-RADAR SYSTEM.—In a one-radar system, the guidance beam is always pointed directly at the target. One or more missiles can be in flight at the same time toward the same target. The traffic handling capacity of the system is limited only by mutual interference between missiles in the beam. Once a missile has entered the beam, no further operations are necessary at the launching site, except to maintain target tracking.

The radar antenna-receiver system in the missile is highly directional, and is most sensitive to signals received from behind the missile (fig. 3-23).

The guidance lobe transmitted by the radar at the control station is detected by this antenna system and fed to a receiver. After the guidance signals are amplified and demodulated by the receiver, they are fed to the computing network in the missile. If the missile is off the scan axis of the guidance lobe, the computer will determine both the direction and the magnitude of the error. It will then generate the correction signals required to bring the missile back onto the scan axis.

The missile is stabilized at some time between launching and shortly after entering the guidance beam, the exact time depending on the type of missile. The missile must be roll stabilized so that it can determine which way it must deflect the control surface in response to the guidance signals in the beam. Proper operation of the missile control system depends on correct missile roll attitude relative to the

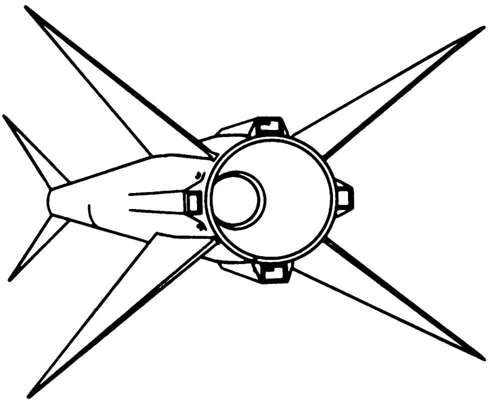

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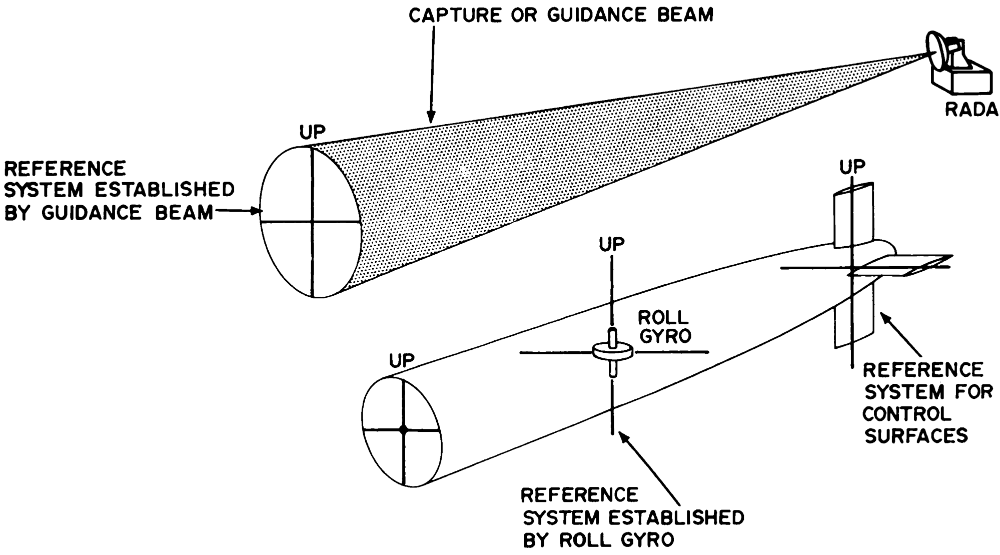
Figure 3-23.—After view of beam rider showing receiving antennas.

guidance beam (fig. 3-24). Radar guidance information may be properly received and processed regardless of roll attitude; but when the missile makes corrections to its flight path, the control surfaces must be properly positioned with respect to the radar beam reference in order to turn the missile in the proper direction.


CAPTURE OR GUIDANCE BEAM
RADAR
UP
REFERENCE SYSTEM ESTABLISHED BY GUIDANCE BEAM
UP
UP
ROLL GYRO
UP
REFERENCE SYSTEM FOR CONTROL SURFACES
REFERENCE SYSTEM ESTABLISHED BY ROLL GYRO

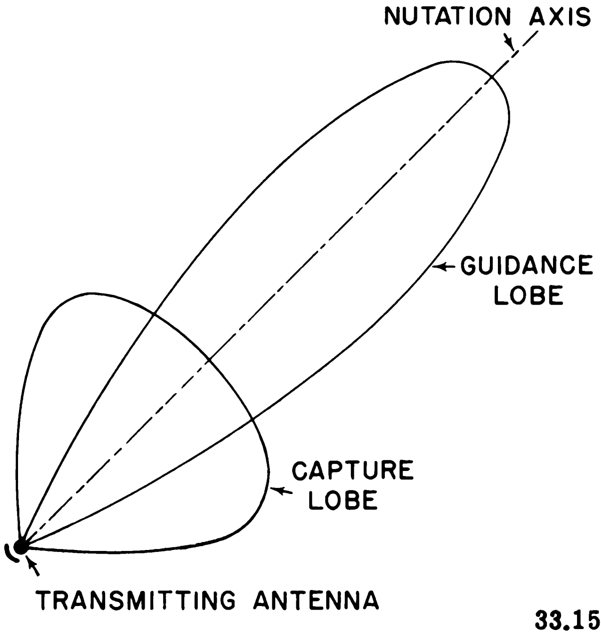
83.23

Figure 3-24.—Radar reference system and missile roll reference system.

So far, we have assumed that there is one beam, the guidance beam. There are actually two—a capture beam and a guidance beam. The guidance radar is located at some distance from the missile launcher. Therefore, the missile cannot be launched directly toward the target, on a course parallel to the guidance beam. Instead, it is launched so that it will CROSS the guidance beam some time after launch. Usually the missile will enter the beam at the end of its boost phase. It will turn toward the target after it has been captured by the beam.

Because the guidance bean is narrow, merely aiming the missile to cross it is not enough to ensure capture. To make capture more certain, a broad CAPTURE BEAM is superimposed on the narrow guidance beam (fig. 3-25). Because the energy in the capture beam is spread out over a large area, its effective range is short.

After the missile is captured, it rides the capture beam for a few seconds. During this time it gets closer to the scan axis of the guidance beam. After a preset interval, a timing device within the missile changes the receiver tuning. The missile will then reject signals from the capture beam and respond only to those in the guidance beam. At capture-guidance changeover the missile should be close to the axes of the two beams, and the changeover should be fairly smooth. Since the missile follows the guidance beam, which in



33.154

Figure 3-25.—Relationship of guidance lobe and capture lobe.

turn follows the target, the missile approaches the target on a curved trajectory until intercept (fig. 3-26).

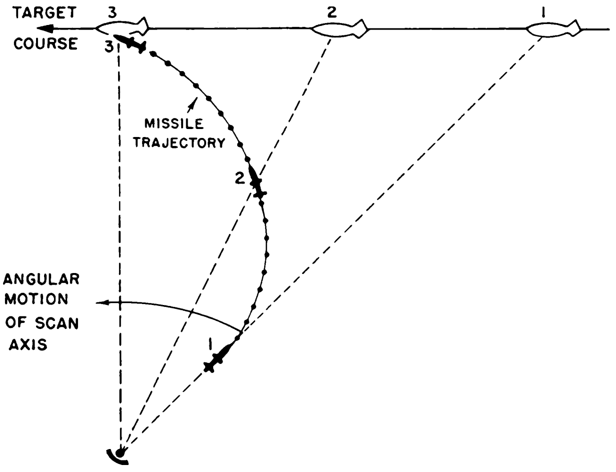


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Figure 3-26.—Increasing lateral acceleration as missile nears target.

TWO-RADAR SYSTEM.—The two-radar beam-riding system uses one radar to track the target and a second radar to guide the missile. Figure 3-27 shows the two-radar system in simplified form. A computer is used between the two radars.

The computing system uses information from the target-tracking radar to determine the trajectory necessary to ensure a collision between the missile and the target. Because the same radar beam is no longer used for both target tracking and missile guidance, the missile need not follow a line of sight path, as was the case with a one-radar system.

The two-radar beam-guidance system is more complex insofar as shipboard equipment is concerned, because of the addition of a computer and a second radar. The equipment in the missile is about the same for either system.

The computer is an important part of a two-radar guidance system. The computer continuously accepts target bearings, ranges, and elevation angles from the tracking radar. From this information it generates a target course and speed, and computes the path that must be followed by the missile. Since the computer receives information constantly, it can alter the missile's path to offset evasive action by the target. The output of the computer controls the guidance radar antenna. Required information is instantly transmitted to the missile by pointing the guidance beam toward the new point of intercept.

Lateral acceleration presents a serious problem when a one-radar guidance system is used. This problem is not present in a two-radar guidance system because the missile need not be directed toward the instantaneous position of the target.

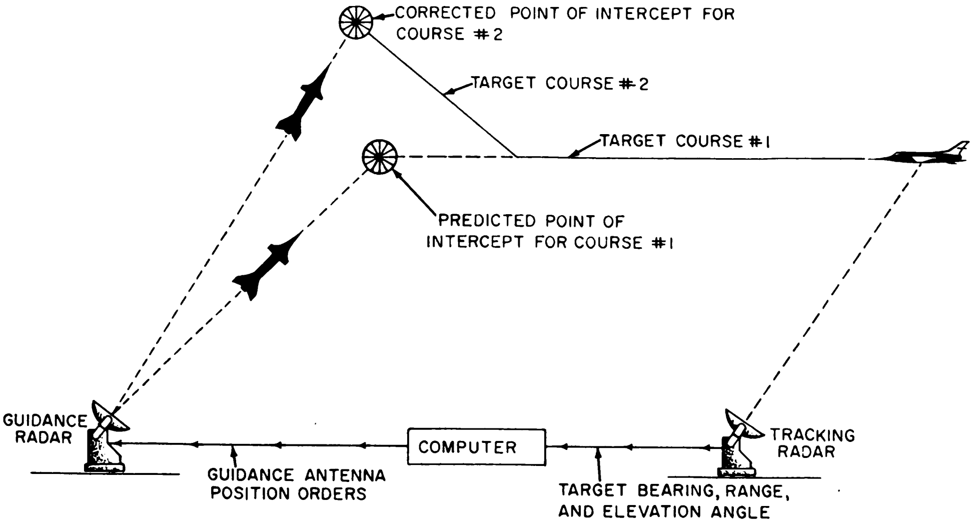
CORRECTED POINT OF INTERCEPT FOR COURSE #2
TARGET COURSE #2
TARGET COURSE #1
PREDICTED POINT OF INTERCEPT FOR COURSE #1
GUIDANCE RADAR
COMPUTER
TRACKING RADAR
GUIDANCE ANTENNA POSITION ORDERS
TARGET BEARING, RANGE, AND ELEVATION ANGLE

Figure 3-27.—Two-radar system.

33.156

Homing Guidance Systems

Homing guidance systems control the path of the missile by a device in the missile that reacts to some distinguishing feature of the target. The homing device, usually located in the nose, detects some type of radiation given off by the target. The guidance system uses some form of LOBING or BEAM-SCANNING technique to generate directional error signals. Lobing and beam-scanning are methods of determining the direction of echoes, and are commonly used in fire control radar. The radiation which the homing device detects may be in the form of heat, light, radio, or radar. It may be generated by the target or by some outside source and reflected by the target.

Homing systems are divided into three types depending on the source of target radiations. These types are: ACTIVE HOMING, in which both the source which illuminates the target, and the receiver which detects the echoes are carried in the missile; SEMIACTIVE HOMING, in which the target is illuminated from some source outside the missile, and the missile receiver utilizes the target reflections; and PASSIVE HOMING, in which the missile receiver detects the natural radiation of the target. The active and semiactive types generally use radar, and the passive type uses heat or light and in some cases homes on a radio or radar transmitter. We are concerned here with the semiactive homing system.

Semiactive Homing Guidance

A missile using semiactive homing guidance receives radar energy along with indirect path. Radar waves are sent out from the shipboard fire control radar. The transmitted waves strike the target and are reflected. Some of the reflected waves travel toward the homing missile. A radar receiving antenna, called the seeker, or seeker head, in the nose of the missile picks up the reflected waves. Then the guidance system causes the missile to home on the target. Briefly, this is the way it does it.

The radar receiver in a semiactive homing missile acts similarly to the beam-rider receiver, but with one exception. Instead of receiving guidance information from a beam, the semiactive missile receives echoes from a target. The missile's homing antenna system locates the target, and automatically tracks it. The predicted location of the target is fed into the missile before launch. The tracking process establishes the line of sight between the missile and target. A computer in the guidance system uses this tracking information to produce steering signals.

LEAD HOMING.—A lead course is established when the path of the missile maintains a constant angle with the path of the target. In lead homing, the guidance system establishes a lead angle with the target and keeps this angle constant so that the missile travels directly toward a collision point, as shown in figure 3-28. The missile completes the final and critical part of the flight path as a straight line.

To effect this course it is necessary for the guidance system to measure the rate at which the angle changes. This may be accomplished by having the homing device point toward the target; and any change in the direction of the target from the missile will cause the homing device to turn. The rate at which it turns can be measured by a rate gyroscope. These additional functions require that the homing system for a lead course be complex.

One of the main limitations of homing systems is that of range. Also homing devices must have high directional sensitivity so they will not be confused by multiple targets. Because of these problems it is necessary to place the missile in the vicinity of the target and pointing toward it. This may require the initial part of the course to be controlled by another type of guidance system, such as the beam rider.

WARHEADS AND FUZES

The guided missile must carry some form of useful burden—a payload—if it is to accomplish its mission. Every action of the missile serves as a means to deliver its payload. In training missiles, the payload often includes telemetering units, which collect data during the flight, convert it into radio signals, and transmit the information to receivers aboard ship. The training missiles carry dummy payloads which have the same physical characteristics as an operational weapon. In its military role, the guided missile's payload consists of one or more WARHEADS and one or more FUZES. The warhead is capable of destroying an enemy target. The fuze is a triggering mechanism used to initiate the actions of the warhead.

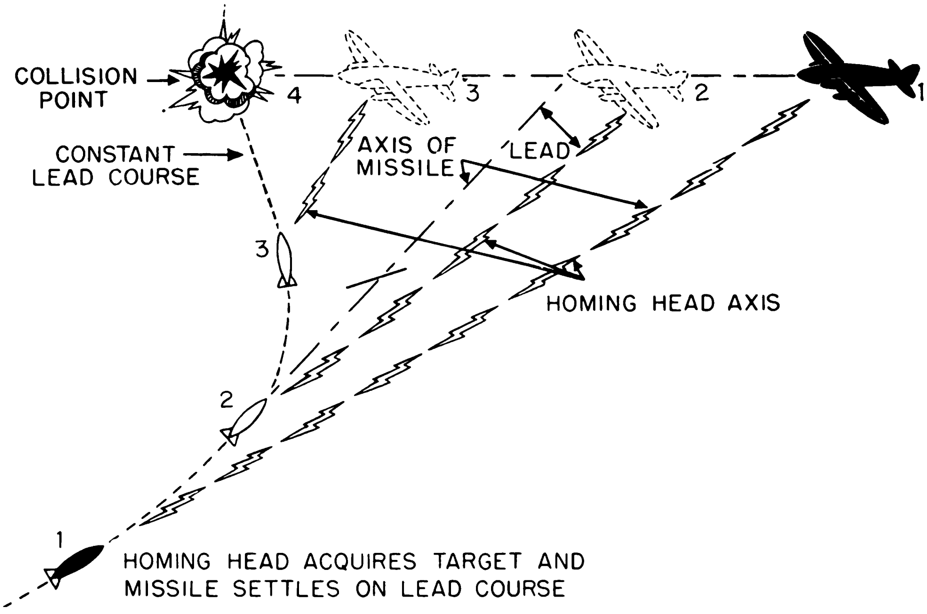

Figure 3-28.—Lead homing. 12.36

TYPES OF WARHEADS

Some of the types of warhead that may be used in guided missiles are blast-effect, fragmentation, shaped-charge, explosive-pellet, chemical, biological, and nuclear or thermonuclear.

BLAST-EFFECT WARHEADS.—This type of warhead causes damage by means of a high-pressure wave or blast, which results from the detonation of high-explosive material. Blast warheads are very effective against ground targets. They are less effective against aerial targets since the pressure wave dissipates rapidly in air.

FRAGMENTATION WARHEADS.—These warheads operate by bursting a metal case containing a high-explosive charge. Upon explosion, the container is shattered into hundreds of fragments which fly out at high velocities; and these are capable of damaging targets at considerable distances from the point of detonation. For this reason, this sort of warhead is very effective against aerial targets. Usually the warhead does not penetrate the target but is detonated by the fuze at some distance from it which allows the full destructive effect to be realized.

SHAPED-CHARGE WARHEADS.—The amount of explosive power released from a shaped charge or "cavity charge" depends on the shape of the explosive material.

Experiments show that if a regular cavity such as a conical hole is molded into the side of an explosive charge nearest the target, the effect on the target is greatly increased. The presence of the hole brings about a concentration of the explosive force in much the same way light is focused into an intense beam by a lens.

EXPLOSIVE-PELLET WARHEADS.—A warhead of this type contains a number of small explosive charges, or pellets, each of which is separately fuzed. When the main warhead is detonated, the pellets are ejected but withstand the force of the explosion and are hurled intact toward the target. The pellets then detonate either on impact or after penetrating the target skin. The total destructive effect combines both blast and fragmentation effects, since blast damage is great when the individual charge is exploded, regardless of whether the explosion occurs at the skin of the target or after penetrating it.

CHEMICAL WARHEADS.—This type may contain either war gases or incendiary materials. Warheads containing gases may liberate any of the well-known types such as mustard gas or lewisite, or some newly developed chemical. The effects produced are either denial of the use of the target area or personnel casualties within the area.

The incendiary warhead contains a material that burns violently and is difficult to extinguish, while covering a large area after realease from the warhead. Incendiary weapons are useful principally against ground targets.

BIOLOGICAL WARHEADS.—A biological weapon delivered by a missile would contain living organisms capable of disrupting personnel activities in the target area by causing sickness or death to the inhabitants.

NUCLEAR AND THERMONUCLEAR WARHEADS.—In this type, destruction and damage result from the processes of atomic fission or fusion. The destructive effects are blast, heat, and radiation. The detonation results in death, sickness, and the denial of the use of large areas as a result of the release of radioactive elements.

Types of Fuzes

The missile warhead is activated by the actions of one or more fuzes, which release the destructive forces after certain conditions have been fulfilled. The type of fuzing employed determines whether the warhead is detonated at a distance from the target, upon impact with it, immediately following penetration, or at some fixed time after penetration of the target skin. The missile warhead is generally detonated in one of the three relations with the target shown in figure 3-29.

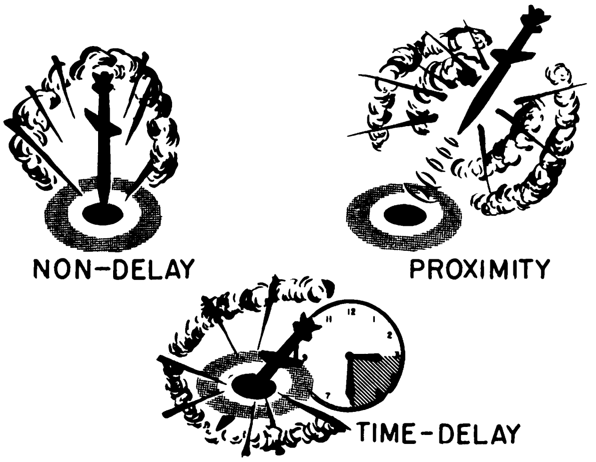

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Figure 3-29.—Types of fuzing.

The most effective type of fuze for a given missile depends upon the nature of the target and the possibilities of the warhead for causing damage. The types often employed in missiles are the IMPACT, GROUND-CONTROLLED, and PROXIMITY fuzes.

IMPACT FUZES.—Impact fuzes are actuated by the inertial force exerted when the missile strikes the target. If detonation takes place at the moment of impact, the fuze is of the NON-DELAY, or INSTANTANEOUS type. If the detonation takes place some time after penetration, the fuze is said to be of the DELAY type.

GROUND-CONTROLLED FUZES.—In ground-controlled fuzes, some device is used for measuring the distance from the missile to the target. The control device is not mounted in the fuze but on the ground; and when the proper space relationship exists between the missile and its target, a signal is sent to detonate the fuze from the control point on the ground.

PROXIMITY FUZES.—Fuzes of this type are actuated by the influence of some property of the target and are detonated at a distance which allows maximum damage to take place. Five general classes of proximity (also called VT, or variable-time) fuzes can be distinguished according to the property to which the device responds. These are radio, pressure, acoustic, photoelectric, and electrostatic fuzes.

Radio fuzes contain miniature transmitters and receivers. In flight, radio signals are radiated, some of which are reflected by the target. At the proper time, the action of the reflected waves causes an electronic switch to close and fire the detonator. Fuzes of this kind have been developed to a high degree of accuracy and dependability. They operate effectively both in darkness and daylight and in all kinds of weather.

Proximity fuzes which respond to changes in pressure generally lack the sensitivity and reliability required for guided missile applications, but in some cases they are useful against surface targets.

Acoustic fuzes, which respond to sound, have the valuable property of all-weather, day-or-night effectiveness; but they also have a disadvantage in that they are subject to local vibrations.

The possibilities of the electrostatic system of fuzing in which the detonating influence is the electric field of the target have also been explored. Attempts to develop the fuze were unsuccessful—probably because of the variable nature of the electrostatic field surrounding possible targets. Photoelectric fuzes react to external light sources and ordinarily are inoperable at night or in conditions of low visibility.

Of these various types of proximity fuzes, the radio system has proved to be the most reliable and effective for missile applications.

MISSILE TESTS

Guided missiles are precision weapons. They are expensive in manpower, material, and money. Moreover, the accelerated pace of modern warfare leaves little room for mistakes. But how can we be sure of a successful flight? One assurance is a shipboard preflight test of the missile's guidance and control system. These tests are held periodically and before firing practices.

The GUIDED MISSILE TEST SET is a self-contained electronic testing and evaluation device which performs GO/NO-GO tests on the flight and guidance components of the missile. The test set indicates whether or not the missile if flight-ready; if not, it shows the probable fault location with one or more missile packages.

Each test set provides two modes of operation, the Missile Systems Test (MST) and a manual testing mode. The MST comprises an automatic self-test and an automatic programmed test of the missile. The automatic self-test ensures that the test set is functioning properly. During MST, the test set programs the missile through a sequence of operations which simulate warmup, launch, boost, beam capture, guidance, and missile reset. The responses of the missile are compared automatically with ranges of acceptable values in the test set, and the results are displayed by GO and NO-GO lamps and FAULT lamps on the front panel. These lamps either indicate a satisfactory missile or identify replaceable faulty packages or sections.

Manual testing permits immediate troubleshooting and checkout of defective packages in the missile. The same test signals that would be applied automatically in a missile test sequence are selected individually by appropriate switches. The results are read on a built-in vacuum tube voltmeter.

CHAPTER 4

THE GUIDED MISSILE FIRE CONTROL PROBLEM

INTRODUCTION

In chapter 2 we discussed the elements of the basic fire control problem and stated the problem for a gun battery. Here we will discuss variations in the basic fire control problem caused by the use of guided missiles. A change in the type of weapon does not change the purpose of a weapon system, which is to destroy a selected target. The three common elements found in any form of the basic fire control problem are present in the missile picture.

These are: the line of sight, the line of fire, and the prediction angle, (lead angle).

We will limit the scope of our discussion to ship-launched guided missiles. These include the surface-to-air beam rider and semiactive homing missiles, and those which use a combination of the two types of guidance.

BEAM-RIDER PROBLEM

In chapter 3 we discussed the beam-rider missile. Here, we will look at the fire control problem as it is seen from a missile launcher firing a beam-rider missile at an air target. Although the basic fire control problem remains the same, the techniques of solving the missile problem are different from those used in solving the gun fire control problem. Moreover, there are some variations in the solution techniques between the one-radar and the two-radar guidance systems. We will state the problem for a one-radar system, and then show the variations in the problem for a two-radar system.

We will divide the beam-rider missile fire control problem into two major phases: the LAUNCHING PHASE and the GUIDANCE PHASE. The launching phase is concerned with directing the beam-riding missile to a predicted point in space called the "capture point," where the guidance devices of the missile and fire control system begin to control the flight path of the missile. The guidance phase of the missile problem is concerned with the transmission of intelligence to the missile to keep it in the beam, and the receipt of this intelligence by the missile, resulting in interception.

The launching phase is analogous to the gun antiair problem. The main difference is the replacement of the future target position in the AA problem with the missile capture position in the beam-rider missile problem.

The missile must be aimed at the capture point so that at the end of booster burnout the missile can be captured by the radar beam. This time from launch to capture (booster time of flight) is a function of booster burning time. The burning time can be considered constant, or at least fairly so; it may vary a little due to propellant temperature changes. Remember in your study of interior gun ballistics that the burning rate of the powder charge was controlled to provide a specific initial velocity of the projectile. The same control of booster propellant burning rate is necessary to keep booster time of flight constant. Now you can see the tie-in between gun and missile ballistics.

The first step in computing the aiming point is to predict how far the target will move during booster time of flight. The result is lead angle due to target motion. But like a gun projectile, the missile is affected by the forces of nature. Wind and gravity are operating on a missile in much the same manner as they operate on a projectile. Therefore, the aiming point must be corrected for these effects.

STATEMENT OF THE PROBLEM

The two basic parts of the beam-rider missile fire control problem are directing the missile into the guidance radar beam, and controlling its flight by signals from the radar.

The missile control radar transmits three radar beams whose axes are coincident. This is illustrated in figure 4-1. One of the radar beams, called the capture beam, uses relatively low power and is much wider than the other beam. The capture beam is used to simplify the capture problem. Once the missile is captured, it is directed into the narrow guidance beam. The missile receives guidance signals from both the capture and guidance beams. The guidance beam, however, is high powered and narrow, to ensure control of the missile's flight. The third beam transmitted by the radar is the tracking beam. This beam tracks the target and establishes the line of sight.

Under ideal conditions, to ensure that the missile would enter the capture beam, the missile and beam axis should be coincident at the time of launch. As this is operationally impracticable, the missile must be launched toward a point in space where it will intercept the capture beam. The first part of the problem—capture—is similar to the AA gunfire control problem in that the missile must be aimed so as to arrive at a specified point on space at a specified time. Since the missile receives no guidance signals until it enters the capture beam, the missile's boost flight must be predicted.

The second part of the missile fire control problem, that of guidance, depends on alignment between reference axes of the missile and the guidance radar. The missile must know which way is up, down, right, and left, in order to respond correctly to guidance error signals. This knowledge is provided by aligning the missile reference axis with the reference axis in the radar.

To state the beam-rider fire control problem we must consider all the factors affecting the POSITION OF THE TRACKING BEAM (which is essentially the LOS), and the BOOST PHASE of the missile flight.

Beam Prediction Problem

The beam prediction problem is concerned with predicting the angular movement of the radar beam axis and thus the line of sight, during the time the missile is under the influence of the booster. The angular movement of the beam is the product of beam angular velocity and time from missile launching until capture (see figure 4-2). Beam angular velocity, or the

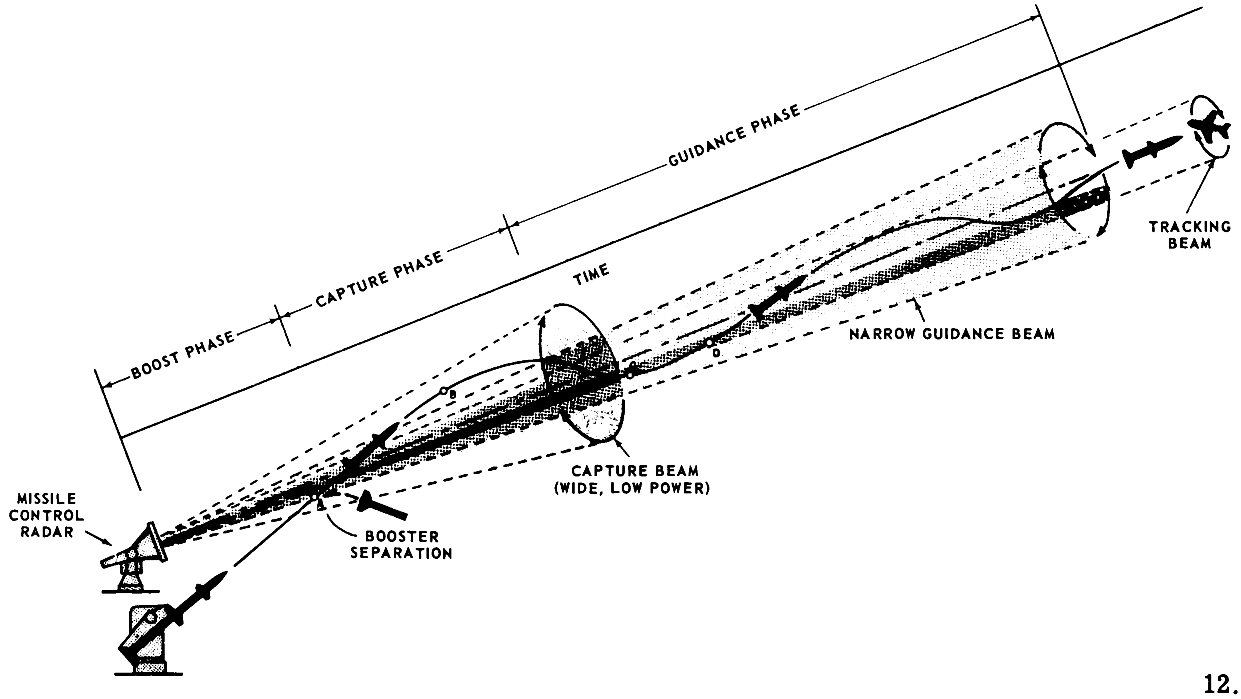

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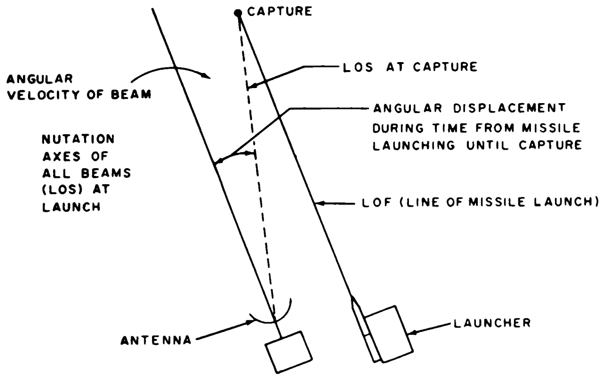
Figure 4-1.—Flight sequence.


CAPTURE
LOS AT CAPTURE
ANGULAR VELOCITY OF BEAM
ANGULAR DISPLACEMENT DURING TIME FROM MISSILE LAUNCHING UNTIL CAPTURE
NUTATION AXES OF ALL BEAMS (LOS) AT LAUNCH
LOF (LINE OF MISSILE LAUNCH)
LAUNCHER
ANTENNA

12.38
Figure 4-2.—Angular displacement between launcher axis and capture beam.

angular velocity of the line of sight, whichever way you want to look at it, depends on the relative motion between the ship and target.

Beam displacement, time of beam capture, and maximum beam rate at capture are three elements which must be considered in the solution of the beam-prediction problem.

BEAM-DISPLACEMENT.—To predict future radar beam position, it is assumed that the target moves at a constant speed and does not change direction. This produces a constant angular velocity of the tracking beam. This assumption does not introduce any appreciable error because the short time of booster flight does not allow much time for the target to change speed or course. Thus the capture beam has a constant angular velocity equal to the angular velocity of the tracking beam as it follows the target.

TIME OF BEAM CAPTURE.—The value of time of flight from launch to capture is equal to the time of booster flight plus an additional correction. It is expected that the missile will be captured by the beam shortly after booster separation, during the time when the missile is not being powered by the booster or by the sustainer rocket motor in the missile. In other words, the missile is coasting. To ensure capture, a correction or lead is made to the line of fire. This correction places the missile ahead of the capture beam at the time of booster separation, allowing the beam to reach the missile when the missile is in free flight (coasting).

Time to beam capture is essentially a constant and is very short—less than five seconds. Booster burnout takes place 3 or 4 seconds after launching, and the missile reaches the capture point a second or so later.

MAXIMUM BEAM RATE AT CAPTURE.—Because of design maneuverability limits, the missile cannot be captured by a beam with an angular velocity above a certain limit at the time of capture.

BALLISTIC PROBLEM

Apparent Wind

The wind acting on the missile is the resultant of true wind due to atmospheric conditions and wind due to ship speed. This resultant wind, called apparent wind, produces a force that tends to turn the missile into the wind.

Gravity

The force of gravity will affect the missile trajectory just as it affects the trajectory of a gun projectile. Gravity effect has been covered in chapter 2, and need not be treated here.

Launcher Motion

The motion of the launcher imparts a velocity to the missile. Launcher motion is equal to the sum of the director's motion tracking the target and the ship's roll and pitch motion. The velocity imparted to the missile tends to make it deviate from the desired flight path.

Propellant Temperature

The burning of the booster propellant produces the thrust to accelerate the missile to operational speed. The thrust is proportional to the burning rate of the propellant which in turn depends on its temperature. The missiles are stored in magazines, to control the propellant temperature and prevent a change of the burning rate and boost time.

LAUNCHER ORDERS

The fire control computer produces the train and elevation orders that are used to control the position of the launcher. The orders are measured with respect to the deck plane, and are proportional to the actual value of the predicted capture angles offset by the ballistic corrections. Since the beams of the radar are coincident, the position of the capture beam, and consequently the capture point, is determined by the target tracking rates. Since the missile's boost time is constant, the prediction of the actual capture can be found by multiplying the tracking rates by the boost time.

The location of the capture point is based on three assumptions: (1) the distance the missile travels in the boost phase is constant, (2) during boost phase the missile will fly true in the attitude established on the launcher, and (3) the tracking rates will remain constant during the boost phase. As you know, the distance traveled by the missile is determined by the burning rate of the booster's propellant which is a function of the propellant's temperature. Variations in the booster propellant temperature (missile magazine temperature) are compensated for by assuming a different boost time.

The second assumption is that the missile will fly in a straight line to the capture point. One type of missile has such built in aerodynamic stability that it will fly straight as an arrow in the attitude established by the launcher. The missile's aerodynamic control surfaces are locked in their neutral position during boost. Other missiles, however, must maneuver during boost to maintain the proper attitude. The missile's attitude during boost is maintained with respect to a reference system within the missile. Prior to launch, the reference system is aligned with the longitudinal axis of the missile, and therefore with the missile's line of fire, (launcher attitude). The missile's steering system maintains this attitude during the boost phase.

The third assumption deals with target motion. The tracking process is continuous, and the tracking rates are corrected whenever an error appears. Thus the predicted capture point is based on tracking rates established at the instant of launch. Since boost time is short, about four seconds, even drastic maneuvers by the target will not normally cause the missile to miss the capture beam.

The launcher's position, and therefore the missile's launch attitude, is established with respect to the deck plane. The roll and pitch of the ship takes the deck plane out of the horizontal plane. The inclination of the deck plane tilts the launcher trunnion just as it does a gun trunnion. Thus the missile launcher trunnion tilt problem is identical to the one we discussed in chapter 2. The effects of deck inclination on the missile's reference system will be discussed under missile orders.

The missile launcher is located at a distance from the fire control radar; therefore, parallax corrections are necessary. The parallax problem is identical to the gun parallax problem covered in chapter 2.

The missile is acted upon by the force of gravity. The control surfaces of the missile function only to keep the missile's attitude fixed in space, and not to compensate for the effects of gravity. Therefore, if no correction were made, the missile would pass some distance below the capture point. To compensate for the effects of gravity, the launcher is elevated so that the missile line of fire is above the capture point. In this manner gravity pulls the missile down into the radar beam at the capture point.

The apparent wind force acting on the missile tends to blow it off course. Since the missile receives no guidance orders during the boost period, the effects of the apparent wind are compensated for by offsetting the launcher in a direction opposite to that of the wind by an amount proportional to its velocity. Consequently, the wind will blow the missile into the radar beam at the capture point.

One of the forces applied to the missile is caused by launcher motion. The direction in which the missile will move is the resultant of all the forces acting on it. To compensate for the deviation that would result from launcher motion, the launcher is offset in the opposite direction by the proper amount.

All the ballistic effects are combined to produce a total effect. The launcher orders are offset from the capture point by an amount equal and opposite to the total effect. To determine the amount of offset, the ballistic effects are resolved into components which coincide with the planes containing the launcher's elevation axis, (normal to the deck plane) and its train axis, (parallel to the deck plane). The offset establishes the aiming point of the launcher in a manner identical to the gun ballistic offset.

TWO-RADAR CONTROL SYSTEM

The beam-capture problem for a missile used with a two-radar control system is basically identical to that of the one-radar system. The missile still must intersect the radar beam at the capture point. But, in the two-radar system, the guidance radar is independent of the target tracking radar. Therefore, the guidance radar can be held stationary after the missile is launched, until it is captured by the beam. This gives the missile a stationary aiming point to hit. This simplifies the prediction problem, and enhances the capture possibility to such an extent that a capture beam is not needed. Only tracking and guidance beam are used in the control system.

When the missile is captured, the guidance radar is programmed to close the angle between the guidance radar and the tracking radar. The fire control computer programs the closure of the angle to obtain the best flight path for the missile. The time needed for the closure of the angle is a factor in the problem. This type of system is normally used against long-range targets where the time is available.

MISSILE ORDERS

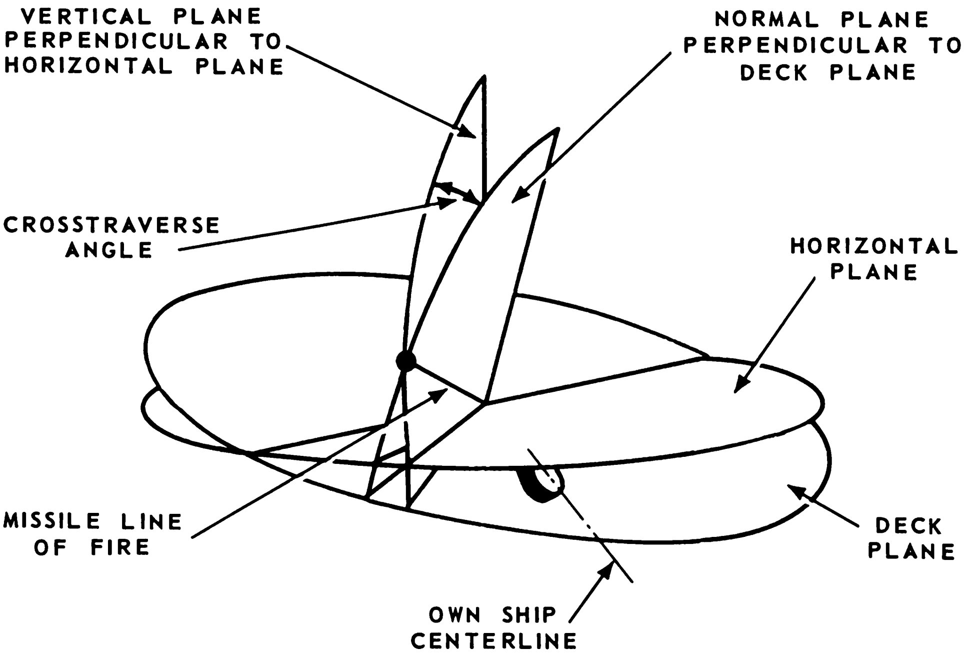
After the missile is captured, it rides the guidance beam to target intercept. Guidance information extracted from the beam is used to control the missile's position in the beam. The missile can interpret this information correctly only if its reference axis is aligned with the reference axis of the guidance beam.

Launcher Cross Traverse Order

The movement of the missile in space is measured with respect to its attitude reference devices (normally gyroscopes). The control radar antenna is space stabilized, and the axis of the guidance beam is measured with respect to the horizontal and vertical planes. Therefore, if we align the missile's reference devices to the vertical plane, both the beam's and the missile's reference systems would be interaligned; that is, both would be aligned to the same reference.

Recall that the missile launcher is positioned with respect to the deck plane, and that the missile's attitude during the boost phase is the same as the launcher's. Before the missile accepts guidance from the radar, its attitutde must be altered to coincide with the beam's reference system. To do this, the missile must know the deviation between the deck and the horizontal plane at the instant of launch.

The fire control computer calculates the cross-traverse angle (fig. 4-3) which is proportional to the deviation between the horizontal plane and the deck plane measured about the


VERTICAL PLANE PERPENDICULAR TO HORIZONTAL PLANE
NORMAL PLANE PERPENDICULAR TO DECK PLANE
CROSSTRAVERSE ANGLE
HORIZONTAL PLANE
MISSILE LINE OF FIRE
DECK PLANE
OWN SHIP CENTERLINE

55.252

Figure 4-3.—Cross traverse angle.

line of fire. The cross-traverse angle order is transmitted to the missile while it is on the launcher. Its value at the instant of launch is stored in the missile.

At the end of the boost phase and just before the guidance system takes command, the prestored cross-traverse angle order is fed to the missile's roll axis reference device. This order causes the missile to rotate about its roll axis until it is aligned with the local vertical. Hence the missile has oriented its roll axis with respect to the same reference as the guidance beam's reference axis. The missile's guidance system can now interpret directional signals extracted from the beam.

Phasing Error Order

The missile's vertical reference must correspond with the radar vertical reference throughout the guided portion of the missile's flight. Maintaining these references in coincidence is termed "phasing." The two main causes of phasing error are the cross-traverse motion of the guidance radar and the turning motion of the missile. The phasing error is calculated in the computer and compensated for in the radar. Since it is one of the problems of missile guidance, it is included here.

The radar antenna mounted on the ship is affected by ship's roll and pitch motion; while the missile in space is not. The radar antenna is stabilized to compensate for the deck displacement out of the horizontal plane, but the cross-traverse motion causes the radar antenna to rotate about its center line axis. This motion shifts the beam reference axis out of coincidence with the missile reference axis. This part of the phasing error is a function of the cross traverse rate of motion for the period of time involved.

MISSILE'S TURNING MOTION.—The missile is assumed to be flying a straight line course, with its thrust axis aligned with the center of the guidance beam's nutation axis. But in actuality this is not the case. The missile tries to stay in a beam that is moving at the tracking rate (plus the beam closure rate in a two-radar system). This results in a trajectory with an angular component. The missile's thrust axis is tangent to this curved trajectory. Therefore, the missile's thrust axis is not coincident with the beam's nutation axis, and an angle is formed between an extension of the two axes. In order for the missile to accelerate toward the center of the guidance beam, this angle must be compensated for. We can look at this angle as if the missile's vertical reference axis had been shifted. The amount of the angular shift is proportional to the angular component of the missile's trajectory, which in turn is proportional to the beam's angular rate of motion. Since we cannot directly correct the missile, this factor is included in the phasing error signal to the radar.

The total phasing error is the sum of the two factors. In the radar the phasing error signal is used to shift the normal guidance beam's modulation to correct for the misalignment between the guidance beam's reference axis and the missile's reference axis. The correction to the phase of the beam's modulation in effect rotates its reference axis to restore the alignment with the missile.

FUZE DELAY TIME.—The fire control computer considers the tactical conditions in the problem, and transmits to the missile on the launcher a fuze delay signal. Fuze delay time computation considers the target's size and speed, plus the range, bearing, and elevation at missile interception, to time the detonation of the missile's warhead for maximum effectiveness.

Missile Firing

We will assume that the fire control system is tracking a target and is ready to launch the missile. The missile is loaded on the launcher rail, and electrical warmup power from the ship is being applied. The launcher is in automatic and is synchronized in a clear firing zone. All the safety interlock switches in series with the missile launching circuit are closed.

When the INTENT-TO-LAUNCH signal is received in the missile, its internal power supply systems, such as the hydraulic and the electrical systems, are started. When the internal electrical power supply reaches a preset level, the missile automatically switches to its own power. Normally, open interlock switches are in series with the missile's internal firing circuit to ensure that the necessary conditions within the missile are met. Examples of these conditions are: the missile timing device is on zero; the gyroscopes are caged or uncaged as required; and the cross-traverse signal is locked at its launch value.

Once the necessary conditions are met, all the interlock switches are closed and the firing circuit is completed to ignite the booster. You can see, from this discussion, that there is a time lapse between the closing of the intent-to-launch signal and the actual launching. In essence we have an automatic count down.

Missile Capture in the Beam

As you know, some beam-rider missile systems use two radar beams for missile guidance; a wide angle, low power beam to "capture" the missile, and a narrow angle, high power beam to "guide" the missile. The two beams are identical in so far as the intelligence contained in them is concerned, and their center line axes are coincident.

To ensure that at the end of its boost phase the missile is receiving intelligence from the radar beam, the wide angle capture beam is used first. This beam will steer the missile toward its axis. Since the guidance beam's center line axis is on the same line, when the missile nears the capture beam's center line it will also be close to the guidance beam's axis. Thus the missile is transferred smoothly from the capture beam to the guidance beam.

While the two-beam system is very effective, it creates a problem; the missile must be able to tell the difference between the two beams, and to distinguish them from any other radar signal that may be present. This is accomplished by a method known as "coding." An example of coding is the pulse group method. The radar transmits a predetermined number of pulses in a group. The spacing between the pulses within a group, and the spacing between groups, are preset. Each beam will have its own code.

The radar receiver in the missile is set to accept a preselected code, and will reject any other signal. The correct code is sent to the radar and missile prior to launch. The capture and guidance beams each have their own code. Because of the difference in codes, the missile's receiver coding must be changed when the missile transfers between beams. The changeover is a timed function of the missile, and will occur a short time after capture. Once the missile's receiver is coded to the guidance beam, it will reject signals from the capture beam.

As we have pointed out, some missile systems use a single beam for beam-rider guidance. In these systems, the accuracy of boost flight must be sufficient to ensure "capture" by the narrow guidance beam. As in the two-radar system, the beam is coded so that the missile can determine the correct beam.

SEMIACTIVE HOMING FIRE CONTROL PROBLEM

Here we will discuss variations in the basic fire control problem for semiactive homing missiles. In semiactive homing a high-powered radar aboard ship illuminates the target, and the missile receives energy reflected from the target. The missile's homing antenna system locates the target by this reflected energy. A computer in the missile's guidance system uses this information to produce steering signals to guide the missile to target interception.

Three lines of sight are present in the problem (fig. 4-4). The line of sight from the ship to the target is established by a tracking radar located aboard ship. The axis of the tracking radar's beam is coincident with the axis of the illuminating radar's beam. To establish the line of sight from the missile to the target, the location of the missile with respect to own ship and the target must be known.

We can divide the problem into three major phases: launch, boost and homing. At the end of the boost phase, the missile must be at a specific point in space. The location of this point and the time of the missile's arrival there, must be known to the fire control computer. The computer uses this information to predict the direction in which the missile's homing antenna must "look" in order to "see" the target.

During boost, the missile receives no guidance signals, and flys in the attitude established by the launcher. Hence the same ballistic problems are present in the launch and boost phases as in the beam-rider problem. There is, however, one exception; at the end of boost, the missile's homing antenna is slewed to a predicted missile-to-target line of sight. The location of this line of sight is predicted by the fire control computer and stored in the missile.

LAUNCHER ORDERS

The train and elevation orders position the launcher so that the missile will be at a specific point in space at the end of the boost phase. The prediction of the location of this point is based on the length of the boost phase and on the tracking rates. As in the beam-rider missile,

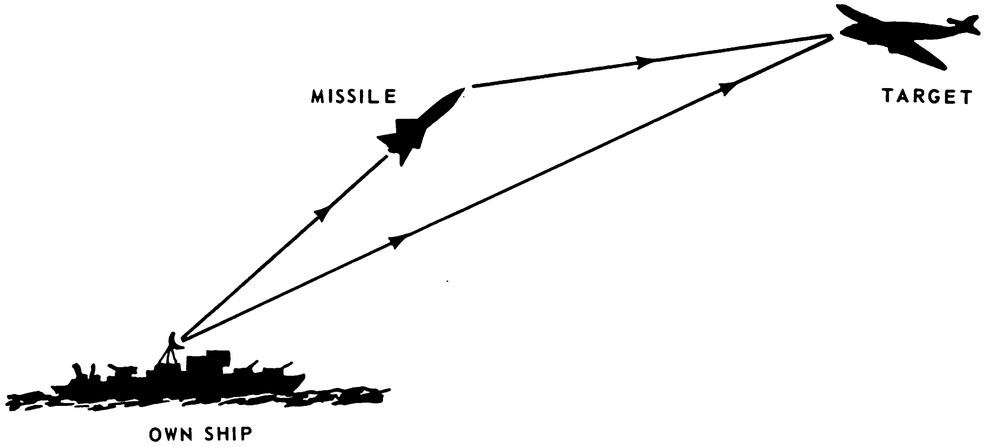


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Figure 4-4.—The three lines of sight in the problem.

boost time is a constant; it may be modified slightly by a variation in propellant temperature. The angles whose values represent the actual position of the missile at the end of boost are found by multiplying the tracking rates by boost time.

The launcher order offsets due to ballistic factors—apparent wind, gravity, parallax, launcher motion, and cross traverse—are handled in the same manner as in the beam rider.

Homing Phase

The homing phase of the missile's flight starts at the end of the boost phase. At this time the homing antenna seeker head must know the approximate location of the target. Seeker-head orders calculated by the fire control computer are transmitted to the missile and their value at launch is stored for later use. The orders are based on the position of the target with respect to the missile at the end of boost.

It is necessary to compute the future position of the target to establish the missile's position. To relate the two positions is a geometric problem. Figure 4-5 illustrates a simplified problem of this type. The larger triangle represents the future position of the target with respect to own ship. The missile is at point 6 in the diagram. The smaller triangle defines the target's position with respect to the missile.

Seeker-Head Orders

The seeker-head antenna has two axes of motion, and therefore two separate orders are necessary to position it. Target position with respect to the missile must be resolved into the two axes. The axes are aligned with the missile's control surfaces and measured with respect to the local vertical. Since the homing system must interpret directional information extracted from the target reflected beam, its reference axis must be coincident with the reference axis of the illuminating radar aboard ship. A cross-traverse order (sometimes called cross-roll) is calculated in the fire control computer and transmitted to the missile. We discussed the cross-traverse order in the statement of the beam-rider problem. The procedure here is the same—the cross-traverse order is used to establish the local vertical reference axis in the missile at seeker-head activation.

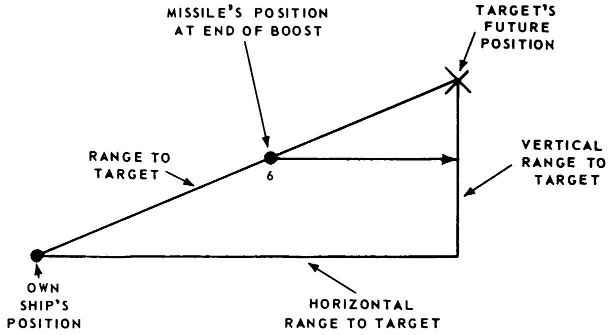

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Figure 4-5.—Simplified diagram used to calculated target position with respect to the missile.

The local vertical is a common reference axis in the fire control radar and computer aboard ship and in the missile. Therefore, the future target position relative to the missile's position at seeker-head activation can be established in the fire control computer with respect to the horizontal and vertical planes, and then rotated to the planes of motion of the seeker-head antenna. The angular values of the future target position relative to the missile are transmitted to the missile as seeker-head orders.

PROPORTIONAL NAVIGATION.—The homing phase of the missile's flight starts with target acquisition by the seeker antenna. The missile's homing system locks on the target reflected energy, and its guidance computer determines the course to steer for target interception. If the missile were to fly directly toward a crossing target, rather than toward a calculated intercept point, it would have to travel farther than necessary. It would have to turn sharply as it approached the target, and would end up in a tail chase, from which the target might escape by radical maneuvering. To prevent this, the missile flys a proportional navigation course. Proportional navigation is a practical method of keeping the missile on a constant bearing course with respect to a maneuvering target. A constant bearing course will ultimately result in a collision.

In a proportional navigation flight path, the missile's heading changes at a rate proportional to the angular rate of change in the missile-to-target line of sight. The rate at which the missile turns toward the intercept point for a given error signal from the seeker head is changed by changing the gain of the missile's steering system in accordance with a variable navigational ratio. At the beginning of homing the gain of the steering system is minimum. This results in a gradual correction to a seeker head error. As the flight progresses, the gain is increased so that just before intercept the gain is maximum. Figure 4-6 shows the resulting flight path of the missile.

The fire control computer calculates a variable navigational ratio based on the predicted time of flight and the missile-to-target closing velocity. The signal is transmitted to the missile and stored until it is used in the homing phase.

SEQUENCE OF EVENTS

We will assume that the missile is loaded on the launcher rail, and warm-up power from the ship is being applied to the missile. When assigned to a fire control system, the launcher is slewed to correspond with the launch orders from the fire control computer. The launcher is positioned so that the missile is pointed at an aiming point determined by the computer. The aiming point is established by predicting the movement of the target during the missile's boost phase, and the offsets due to missile ballistics. While on the launcher, the missile is receiving and storing orders from the computer. The orders are compensations for conditions in the problem, and the missile's flight characteristics and program.

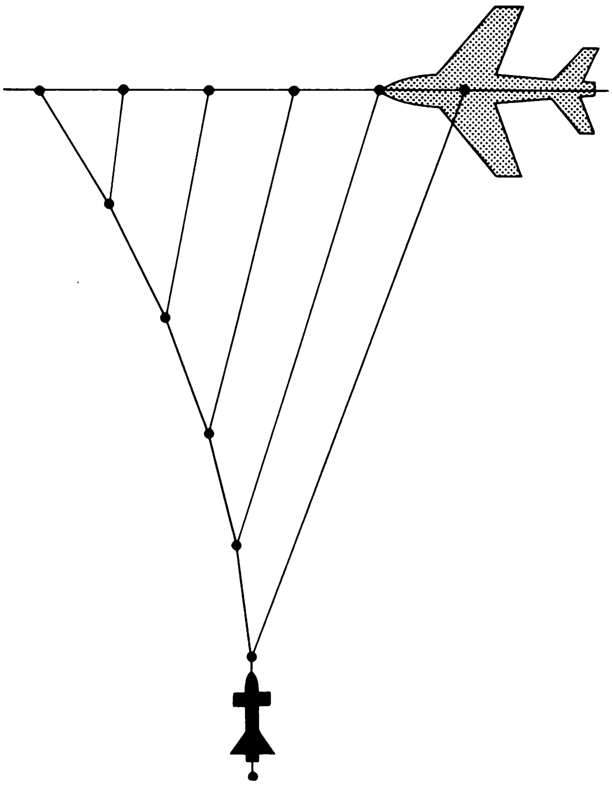
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Figure 4-6.—Proportional navigation flight path.

If all the firing conditions are met, the missile is launched by the INTENT-TO-LAUNCH signal. In principle, the conditions required to launch the missile are the same as those we discussed for the beam rider. Upon launch, the missile enters the boost phase. During boost the missile does not receive guidance signals, and its flight path is determined by the launcher's attitude. At the end of boost the missile is at a precalculated point in space and traveling at supersonic speed. The homing system is activated, and the seeker antenna is slewed to the predicted line of sight to the target.

Missile homing starts when the target is acquired by the missile's radar receiver. The illuminating radar aboard ship is the initial source of the target reflected energy. The radar beam is frequency modulated so that the missile receiver can extract and interpret tracking information about the missile-to-target line of sight. The radar beam is coded so that the missile receiver can identify its illuminating radar and the selected target. A rear antenna on the missile receives a sample of the illuminating radar's energy directly from the ship. The sample is used to compare the coherency of the front and rear signals.

The missile locks on the target reflected energy. The seeker antenna is kept pointing directly at the target by signals from the radar receiver's error detector. When the target maneuvers, or the missile drifts off course, the seeker antenna is no longer pointing directly at the target. The radar receiver's error detector senses the change in the missile-to-target line of sight and drives the antenna back on to the target. At the same time, the movement of the antenna is used to correct the missile's course. The variable navigation ratio signal changes the gain of the control system, and thus the missile's response to an error. At long ranges the missile's response is gradual and smooth, while at short ranges the response is rapid and decisive. The problem ends when the missile's proximity fuze triggers the warhead.

COMBINATION GUIDANCE SYSTEMS

Here we will discuss long-range missile systems that use both beam rider and semiactive homing guidance. The beam-rider guidance technique is accurate at short and medium ranges, but its accuracy decreases as the range increases. At long range the guidance beam is wide, and guidance is less accurate. On the other hand, as a semiactive homing missile approaches its target the reflected guidance signal becomes stronger, and the guidance system becomes more accurate. Therefore, a combination of the two guidance systems can be used to provide accurate control throughout the flight of a long-range missile. The missile is boosted into a guidance beam, and rides the beam while its accuracy is high. Before the beam looses too much accuracy, the missile is shifted to homing guidance, and it then homes on the target until intercept.

We can divide the problem into three major phases: boost, midcourse, and terminal. In the boost phase the missile is accelerated to operational velocity and flies a predetermined flight path. The boost phase is from launch to booster burnout. In the midcourse phase the missile is riding the guidance beam. The midcourse phase guides the missile to within homing distance of the target. The midcourse phase is between beam capture of the missile and target acquisition by the missile's homing system. In the terminal phase the missile has acquired the target and homes in on it. The terminal phase is between target acquision and intercept.

The shipboard fire control system and the missile must contain equipment for both types of guidance. Thus the fire control radar must transmit a target tracking beam, a guidance beam, and an illuminating beam. The tracking beam and the illuminating beam axes are coincident. The guidance beam is programmed by the fire control computer to become coincident with the illuminating beam toward the end of the midcourse phase. The missile has separate antenna and receiver systems for beam rider and homing guidance.

The fire control computer must compute the beam capture point at the end of the boost phase for beam rider guidance, plus target position with respect to the missile at the end of the midcourse phase, if the homing system is to acquire the target. The computer also determines when missile guidance should be shifted to homing. A radar beacon in the missile transmits to the ship fire control system its range from the ship. Missile range is used in the fire control computer to keep track of the missile's position with respect to own ship and the target. The computer evaluates this information and orders the radar to send a command signal to the missile to shift guidance.

STATEMENT OF THE PROBLEM

A statement of the problem of the missile's boost phase deals with the factors affecting the establishment of a point in space at which the missile will intersect the guidance beam. Thus the basic problem is identical to the one we discussed for the beam-rider missile. We will assume that a two-radar control system is used with this missile.

Midcourse Phase

The midcourse phase starts with the missile's capture in the beam. The missile rides the beam through the major portion of its flight. The beam guidance signal received in the missile energizes the missile's beacon transmitter. The beacon transmits signals back to the guidance radar to show that the missile is in the beam, and to indicate the missile's range from the ship. The fire control computer uses missile range to compute the program for the guidance radar convergence with the illuminating radar, and to determine missile-to-target range. Missile-to-target range is used to determine when to shift missile guidance. A command signal, originated in the computer, is sent via the guidance radar to the missile, ordering it to shift to the terminal phase.

Terminal Phase

Upon receiving the command signal, and while still beam riding, the missile's homing system starts to search for the target. The homing system, once it locks on the target-reflected energy, will track the target during the entire terminal phase. The source of the energy reflected from the target is, of course, the illuminating radar aboard ship. As the missile nears the target, the fuze detonates the missile's warhead.

CHAPTER 5

OVERVIEW OF A SHIPBOARD WEAPONS SYSTEM

This chapter will give you an overview of a shipboard gun and missile weapon system. The treatment is brief for several reasons. First, to describe the physical features and functioning of components of a weapon system in detail would require several volumes. Second, security requires that we describe the functions of certain equipments in very general terms. In some cases values of range, target height, target speed, and other characteristics of the target and equipment have been left out. But this chapter will provide you with the background you will need to study the many weapons systems now in the fleet.

WEAPONS SYSTEM CONCEPT

You have already studied the fundamental fire control problem. Now you will study some of the equipment used to solve that problem.

The effective use of any weapon requires that a destructive device (usually containing an explosive) be delivered to a target—usually a moving target. To deliver the weapon accurately, we must know both the location and the velocity of the target. Many targets now travel faster than sound, and must therefore be engaged at great distances. Against such targets, a weapon is most effective when it is used as part of a weapon system. A weapon system is the combination of a weapon (or multiple weapons) and the equipment used to bring their destructive power against an enemy.

A weapons system includes:

1. units that detect, locate, and identify the target.
2. units that direct or aim a delivery unit.
3. units that deliver or initiate delivery of the weapon to the target.
4. units that will destroy the target when in contact with it or near it. These units are usually termed weapons.

DETECTING UNITS

The first steps in using a weapon system to solve the fire control problem are to detect, locate, and identify the target. Initial contact with a surface or air target may be visual, or it may be made by radar. It is difficult to detect a target visually at long range, or even at short range when visibility is poor. For that reason, targets are usually detected by search radar. Search radars, as you know, keep a large volume of space around your ship under continuous watch. They give the ship fairly accurate information about the target's position, even when the target is hidden by for or darkness. To determine a target's position we must know its range, its direction from the ship, and, for an air target, its elevation. Radar gives all three of these coordinates. (Radar has certain disadvantages, too. For example, it can be detected by an enemy at about 1.5 times the range at which it can pick up an enemy target.)

Optical devices are used as a source of information on slow-moving targets at relatively short range. They are useless against missiles or jet aircraft, which must be engaged while they are still beyond the range of optical instruments.

After we have detected and located a target, we must identify it. How can we identify a target that may be several hundred miles from our ship? The answer lies in a device called IFF (Identification, Friend or Foe). Radar alone cannot tell the difference between a friendly or enemy target. But the IFF equipment can challenge an unidentified target, and determine from the answer whether the target is friendly. The equipment consists of two major units—the challenging unit which asks the question, friend or foe, and the transponder which answers the question. IFF equipment is used in conjunction with search radar, and sometimes fire control radar. Briefly, this is how it works. To challenge a target you press a switch attached to the radar. The IFF transmitter will then send out a pulse of low power radio energy toward the target. If the target is friendly it will carry a transponder, which consists of a receiver and a transmitter. When the receiver picks up a challenge, it causes the transmitter to send out an answering pulse or pulses. The answer is usually a coded message. It is picked by the challenging unit's receiver and sent to the indicator of the search radar.

CONTROL UNITS

Control units in a weapon system develop, compute, relay, and introduce data into a delivery unit, a weapon, or both. They direct, control, or guide the weapon (destructive device) to the target, and cause it to function in the desired way. These units form the heart of the weapon system.

Types of Control Units

The devices that perform the control functions include: DATA TRANSMISSION SYSTEMS that send target position information developed by the detecting units to the rest of the weapon system, and convey other data among the components of the weapon system. Examples are synchro, resolver, and potentiometer circuits.

COMPUTER DEVICES to process the input data from the detecting units and other sources, and put out the aiming and program instructions that cause the weapon to reach its target. Examples are rangekeepers and computers.

DISPLAY UNITS that display information at various locations on the ship. These are generally electronic, electromechanical, or optical devices.

DIRECTING DEVICES which, with the aid of detecting devices, establish target location. Directing devices can also function to directly or indirectly control missile flight. Examples are gun and missile directors, and radar sets.

REFERENCE DEVICES such as stable elements, which establish reference planes and lines to stabilize lines of fire, lines of sight, and other references. These units usually are gyroscopically controlled.

DELIVERY UNITS

Broadly speaking, delivery units launch or project destructive units toward the target. Examples are guns, missile and rocket launchers, torpedo tubes, and depth charge projectors. Don't think of these devices as weapons. The term WEAPON is properly applied to the destructive unit that is launched or projected. Thus a guided missile launcher is not, strictly speaking, a weapon; the missile itself is the weapon.

To be effectively employed against their targets, all weapons must either be aimed at their targets or be programmed during flight; they may require both aiming and programming. Programming is the process of setting automatic equipment to perform operations in a predetermined step-by-step manner. Aiming and programming are done at or before the time of launching, either by or through the delivery device. This function is characteristic of all delivery devices, even the simplest. Aiming the destructive device (weapon) at the target may be done simply by positioning the delivery device (a gun barrel or launcher guide arm, for example). Or it may be done without aiming the delivery device, by placing program instructions in the weapon. Some missiles are programmed to start searching for the target after the launching phase is over. Examples of other programmed functions that could be performed in the weapon are ignition of propulsion units and arming of the warhead after a designated number of seconds in flight.

Types of Delivery Devices

GUNS, which provide all the propulsion energy to their projectiles, direct (aim) the projectiles by positioning the gun barrels.

MISSILE LAUNCHERS, which retain and position missiles during the initial part of the launching phase, and, by means of attachments to the launcher, feed steering, vertical reference, and program information into the missile up to the instant of launch. Of course there are other types of delivery devices, such as torpedo tubes, depth charge and thrown weapon projectors, and rocket launchers. But guns and missile launchers are most important to you as an FT. You will be required to understand their function in the weapons systems.

DESTRUCTIVE UNITS

The end purpose of detection units, delivery units, and control units is to cause the destruction unit to intercept or pass near the target. It is then the function of the destruction unit to destroy or inflict maximum damage on the target.

Basic Weapon Components

All weapons have these components:

1. A CONTAINER or BODY which houses the internal components. The body may have such other functions as piercing armor, breaking up into high velocity fragments when the weapon or projectile explodes, or improving the weapon's ballistic characteristics by means of fins or streamlining.
2. A DETONATING DEVICE (called a fuze, an exploder, a detonator, etc.) which initiates explosion at the proper time, and includes safety devices to prevent premature explosion.
3. A PAYLOAD which is the "reason for being" of the weapon or projectile. The payload usually consists of high explosive or nuclear material.

Weapons of some types have their own propulsion systems. The outstanding examples are guided missiles, torpedoes, and rockets. With the exception of rockets, weapons that have a propulsion system also contain guidance and control systems.

REPRESENTATIVE WEAPONS SYSTEM

Figure 5-1 represents a typical shipboard weapons system. The equipments making up each of the four categories of functional components are enclosed in separate blocks. We will introduce and discuss the four groups of equipments in the order in which they operate to solve the fire control problem.

TARGET DETECTION, LOCATION, AND IDENTIFICATION

The first contact with an airborne target is usually made by air search radar. These radars are designed to keep a large aerial volume under nearly continuous observation. Jet aircraft travel at high speed, and may launch guided missiles against our ships from a great distance. This requires that our radar search be carried out to long range. To cover the necessary area, search radar uses a wide beam. In addition, most search radar antennas rotate as they search. Targets show up on the radar's target display indicators as alternately fading and brightening spots. It is difficult to determine target range, course, and speed from these spots. All of these factors limit the accuracy with which search radar can provide information about target position. For target information of the required accuracy, we must depend on fire control radars. We will discuss these radars later in chapters 12, 13, and 14.

After the search radar has detected a target and determined its approximate location, the next step in the development of the fire control problem is to identify the target. The problem of recognizing and identifying a friend or foe is as old as warfare. Passwords, flag hoist signals, and even the uniforms we wear are identification devices that have been developed through the years.

In modern warfare the identification problem is urgent. Radar systems present targets in the form of spots or spikes (called echoes) on a radar screen; but friendly and enemy targets look alike on the screen. Furthermore, high speed planes and guided missiles give us very little time to solve this problem. And when friendly fighter aircraft pursue enemy planes to within weapon range of our ships, the identification problem is acute.

As we said before, IFF is the device we use to determine whether the target is a friend or foe. When you can, talk to an ET about IFF, and about the various search radars on your ship. Although search radar and IFF are not part of the fire control system, they are components of your ship's weapons system. And you, as an FT, should know the part they play in the functioning of that system.

Before we leave the subject of the major equipments that fall in the category of detection, location, and identification units, we want to emphasize that solution of the fundamental fire control problem begins with detection of a target. The next step is to locate it. And the final step in this initial phase is to identify it as friend or foe. These three steps combine to form the first phase in the functioning of a weapon system. At this point you should begin to see that you must think in terms of a complete weapons system in order to understand the functioning of each individual component in the system.

Now let's consider the CONTROL UNITS in group (2) (fig. 5-1). This group requires careful

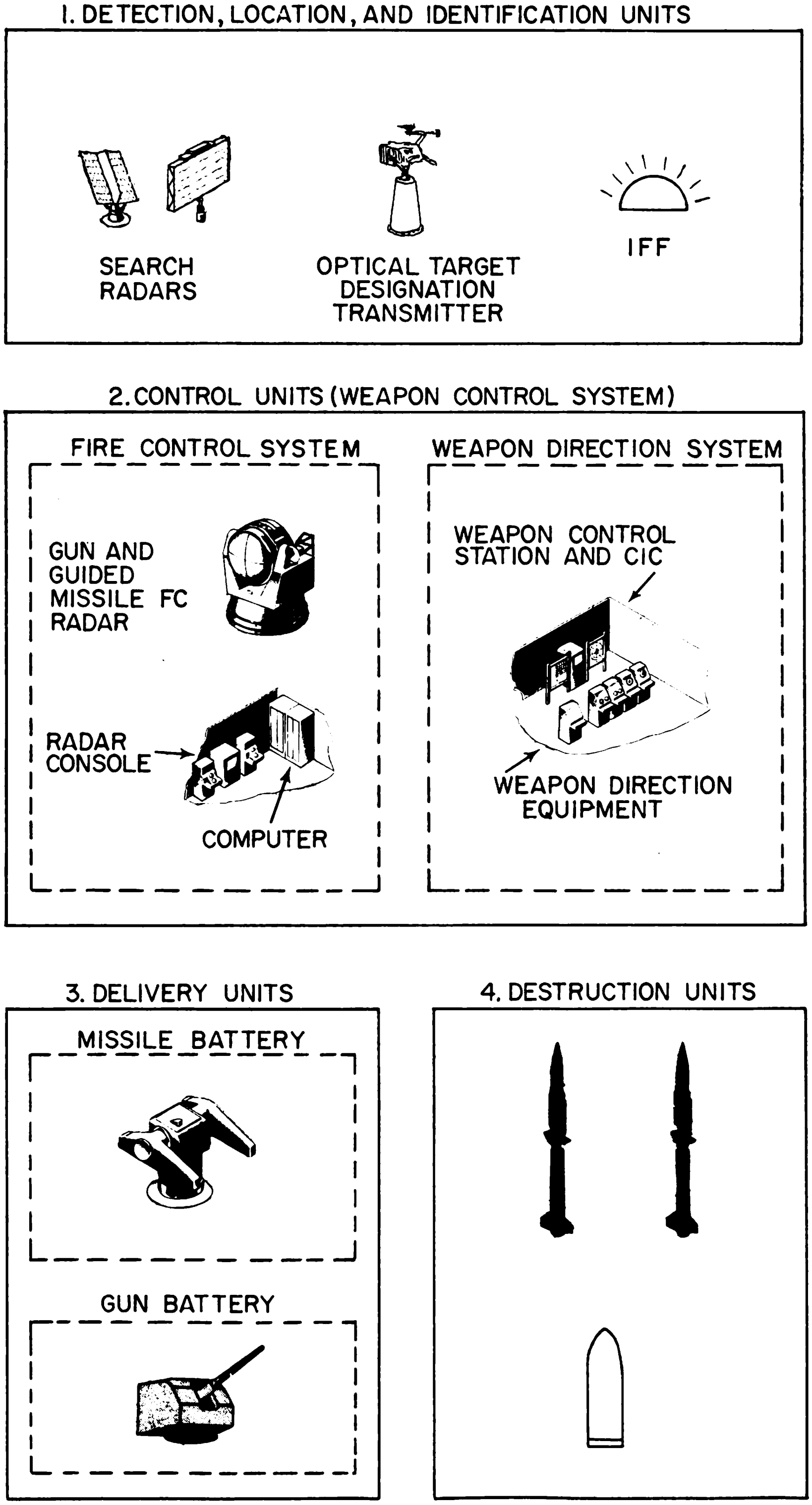
1. DETECTION, LOCATION, AND IDENTIFICATION UNITS
SEARCH RADARS
OPTICAL TARGET DESIGNATION TRANSMITTER
IFF
2. CONTROL UNITS (WEAPON CONTROL SYSTEM)
FIRE CONTROL SYSTEM
GUN AND GUIDED MISSILE FC RADAR
RADAR CONSOLE
COMPUTER
WEAPON DIRECTION SYSTEM
WEAPON CONTROL STATION AND CIC
WEAPON DIRECTION EQUIPMENT
3. DELIVERY UNITS
MISSILE BATTERY
GUN BATTERY
4. DESTRUCTION UNITS

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Figure 5-1—Representative weapons system.

attention; it includes the equipment you will be working with during your entire Navy career.

THE WEAPON CONTROL SYSTEM

Once the air search radar detects and roughly locates the target, and the IFF equipment has determined whether it is a friend or foe, the target information from these sources is sent to the equipments that we have called control units. These units include fire control radars, directors, computers, weapon direction equipment, stable elements, and many other mechanical, electrical, and electronic instruments.

Traditionally, the systems of equipment used for the control of a particular battery of guns, torpedoes, or other weapons, have been known as fire control systems. But the complexity of guided missiles has required the introduction of new fire control instruments, and new terms to describe them. In the following paragraphs we will define some of these terms.

All the units that are enclosed by the solid line in block (2) of figure 5-1 form a WEAPON CONTROL SYSTEM. A weapon control system is defined as a group of interconnected and interrelated instruments that are used to control the delivery of effective fire on selected targets. The system is composed of a WEAPON DIRECTION SYSTEM and one or more FIRE CONTROL SYSTEMS.

Weapon Direction System

A WEAPONS SYSTEM begins to function as soon as a target is detected. However, a FIRE CONTROL SYSTEM begins its functioning by determining target position with all possible precision, so that a line of fire can be established. Before a fire control system can establish a line of fire, certain preliminary processes must take place within the weapon system. These processes are:

1. Detection of a target by search radar or other devices.
2. Identification of the target by IFF or other devices
3. Evaluation of the target
4. Designation of the target to a fire control system
5. Acquisition of the target by a fire control system

The target position and identification information obtained during the first two processes is sent to the CIC (Combat Information Center), and to the WCS (Weapon Control Station). These two organizations of equipment and personnel may be in the same compartment or in separate locations. Here, we will consider them to be in the same compartment. This compartment also contains the units that make up part of the Weapon Direction System (WDS). This particular group of equipments is known collectively as WEAPON DIRECTION EQUIPMENT (WDE). The WDE, and units that support its function, make up the Weapon Direction System of a ship.

The purpose of the WDS is to perform those functions that are required during three phases of a tactical situation. During the first phase, the equipment provides electronic means for the display of targets detected by search radars, and it provides devices for selecting and initially tracking the targets that show up on the displays. These displays are similar to the PPIs (Plan Position Indicator) that you have read about in Basic Electronics, NavPers 10087-A. Targets show up as bright pips or dots on the face of the scope.

As the tactical situation develops, and the targets get closer, the system provides means for evaluating the situation and assigning a fire control system or systems to acquire and track designated targets. This is the second phase in the tactical situation. The third and last phase requires that weapons be assigned by the WDS to the fire control system that is tracking the target. Before weapons are assigned, the tactical situation must be reevaluated.

So far in this discussion, we have introduced three new terms: evaluation, designation, and acquisition.

Target EVALUATION is concerned with these questions:

1. What does the target intend to do? Is it going to pass close to the ship for observing, or is it going to launch an attack?
2. How threatening to the ship's safety is the target? If its obvious intent is to attack, how much time does the ship have to launch a counterattack? And what weapons should the ship use to repulse the target?
3. What kind of attack is the target capable of launching? If the target carries missiles, the ship must launch weapons that will reach the target before it can launch its missiles.

There are other factors involved in evaluating a tactical situation, but these sample questions should give you some idea of what the term "evaluate" means. More examples will turn up later in this chapter.

The equipment in the weapon direction system presents a complete visual picture of the tactical situation. It displays all the targets that have been detected by the search radars. Each target must be evaluated with respect to the overall defense picture. Decisions are made to bring the ship's weapons to bear on the most threatening targets. These selected targets must be assigned to the appropriate fire control systems. The assignment process includes two functions—designation and acquisition.

DESIGNATION is the step taken to assign the tracking element (director's radar or optical equipment) of a fire control system to a particular target. On the basis of target evaluation and the availability of fire control systems (some of which may be disabled, or busy with other targets), a decision is made to assign a fire control system to the target. This is usually done by pressing a button to activate circuitry that transmits target position information from the weapon direction system to the antenna positioning circuits of a radar set, or the power drives of a director. These units automatically move the radar antenna to the designated position. If the designation is inaccurate, the director must search for the target.

The searching process may last for a second or longer, depending on the accuracy of the designation information and other factors. Once the director has found the target and starts to track, it can be said that it has acquired the target.

ACQUISITION by the tracking device is the process of accepting a designation acquiring the target, and starting to track it. A target is acquired when the radar has "gated" it, or the crosshairs in the director sights are on it.

In the preceding discussion we indicated that the WDS was further subdivided into the weapons direction equipment, and other equipment related to the overall function of the weapons direction system. In the following articles we shall take up the units that make up the weapons direction system.

TYPICAL WEAPON DIRECTION EQUIPMENT

The weapon direction equipment includes displays and controls for the evaluation of target data, and for the selection and engagement of targets so as to ensure the most effective use of the gun and missile batteries. A typical WDE consists of one or more TARGET SELECTION and TRACKING consoles, a DIRECTOR ASSIGNMENT console, a WEAPON ASSIGNMENT console, and the necessary cabinets to house power supplies and computer units.

Target Selection and Tracking Console

Figure 5-2 shows a typical target selection and tracking console. Regardless of the mark or modification, they all have the same general function. The console is used for selecting and tracking targets detected by search radars. The principal indicator is a PPI that displays the true bearing and slant range of targets picked up by a selected search radar. The primary controls are a pantograph arm for selecting and tracking targets, and pushbuttons for assigning targets to tracking channels. Other controls are provided for selecting various search radars for the PPI display, for selecting the range scale, and for inserting target position and height data into the tracking channels.

Targets are displayed on the scope as radar video (pips). To select a target and assign it to a tracking channel, you position the pantograph sighting ring over the target pip and then press a channel button. Pressing the button gains electrical access to that channel, and simultaneously causes an identifying channel letter to appear next to the target pip. Successive corrections of pantograph position develop target course and speed in the tracking channels.

Director Assignment Console

The primary purpose of this console is to provide the information display and controls required to assign fire control systems to the targets being tracked by the target selection and tracking console operator, when it is determined that a specific target or targets should be engaged. Figure 5-3 shows the panel layout of the director assignment console for our basic WDE. Two plots are provided on the face of the console—a plan plot on the left, and a multipurpose plot on the right.

The plan plot shows three range rings, and indicates true bearing with north at the top. Each target being tracked by the target selection and tracking console appears on the display as a letter, corresponding to the tracking channel from which it originates. The figure

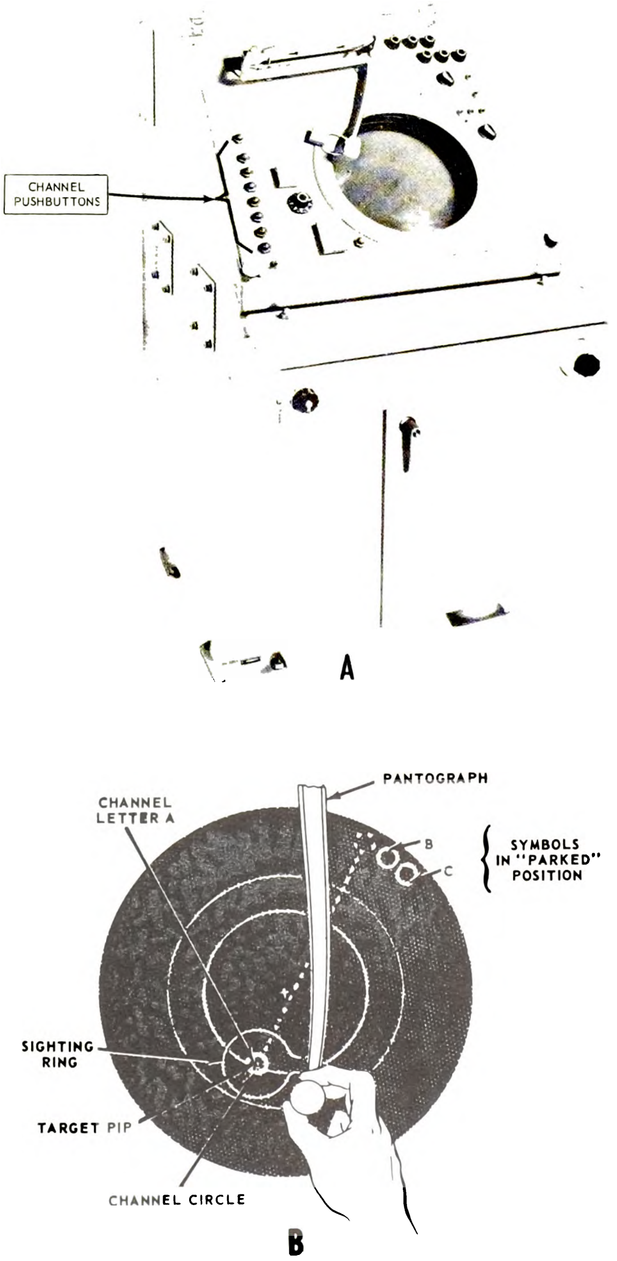

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Figure 5-2.—A. Typical target selection and tracking console; B. Scope display.

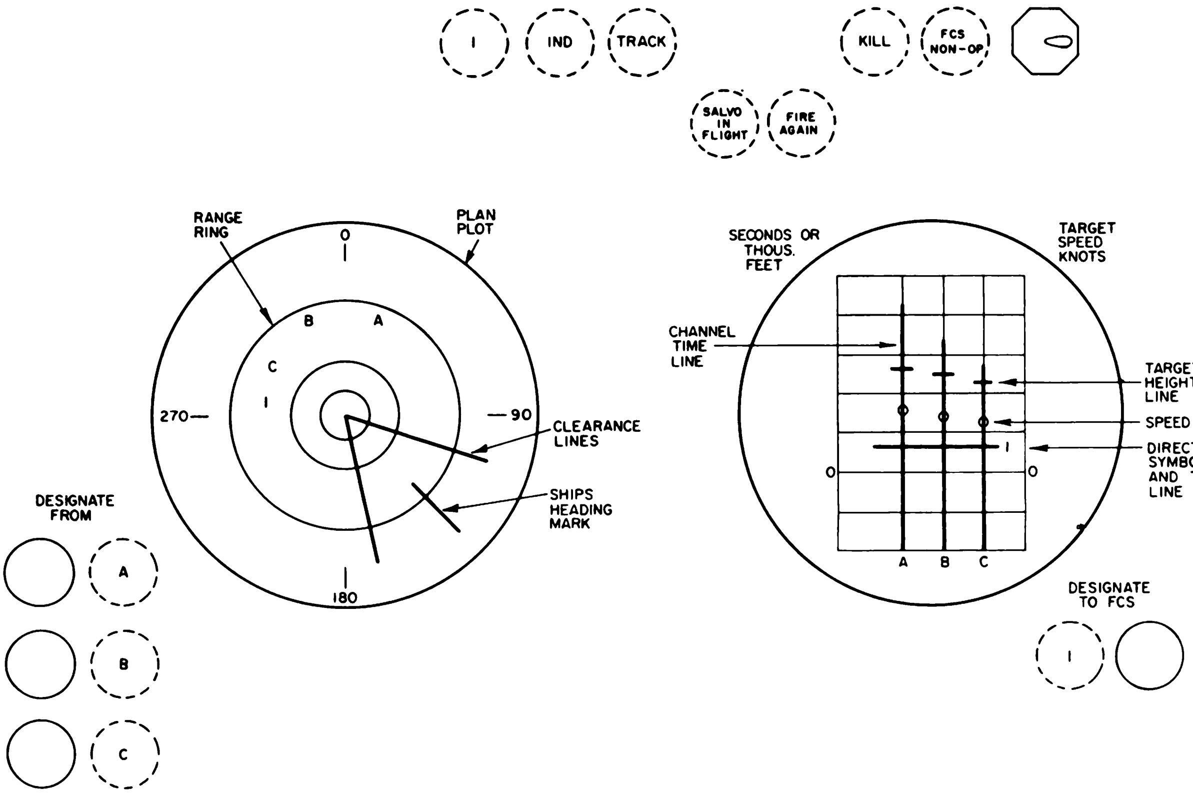
shows that tracking channels A, B, and C are tracking three separate targets. The straight line associated with target A indicates the course of this target. The number 1 indicates the position of the director in the fire control system. If the weapon control system had more than one fire control system, these additional systems would have associated numerals. A ship's heading marker, and radial clearance lines on either side of it, are presented electronically and rotate when the ship changes course. The sector between the two clearance lines indicates the region into which we may not launch missiles because of danger of striking the ship's superstructure.

The multipurpose plot is used primarily for making time comparisons. These comparisons help the operator to decide which of several targets to designate to a director, and to plan the future handling of targets that cannot be assigned immediately. Once the director acquires the target and begins to track it, the fire control system is busy. During this time the operator, with the aid of the information displayed on the plot, can decide which target is next in line for assignment.

The multipurpose plot also indicates the speed and height of targets in the tracking channels. As you can see in figure 5-3, it is divided into three vertical lines—each line representing a tracking channel. All changes in indications take place vertically, and you can read the values indicated as you would read a thermometer.

The vertical lines show, for each target, the time within which the radar set must be assigned and a missile fired in order to intercept the target before it can reach its Estimated Weapon Release Range (EWRR). The EWRR will vary depending on the type of payload the enemy is carrying and on how accurate you guess what the payload is. For example, if you guess that the target's payload is an air-to-surface beam-rider missile, the EWRR might be on the order of 25,000 yards. At the left of the plot you can read how much time you have to assign the target, solve the problem, and load and fire a missile salvo, the intercept the target before the target can release its missiles. This points up the need for quick evaluation. In conjunction with the plan plot, the multipurpose plot provides the necessary information to speed up this process. It relieves the operator of the necessity of remembering how much average time each component in the weapon system requires to perform its function under varying conditions.

The scale used to measure assignment time is also used with the height line. The height line is a short horizontal bar which moves up and down the vertical channel line as target altitude changes (fig. 5-3). In this case the number (not shown in the figure) represents



12.43

Figure 5-3.—Director assignment console display.

thousands of feet. To the right of the display is a target speed scale (marked knots) which is used in conjunction with the speed circle. The speed circle rides up and down to indicate target speed.

The long horizontal line shown in this plot represents busy time for the fire control system. When the system is not acquiring or tracking, the time line and director symbol number rest at zero time. But when the director is assigned a target, the time line and symbol move up to indicate the time during which the director will be busy with that target; they slowly move down as time elapses. After a missile salvo is launched, the line and symbol continue to move downward until they reach zero. The missile should have intercepted the target, and the fire control system is free to be assigned a new target.

Above the two display plots is a field of lamps relating to the gun and missile fire control system. The lamp with the numeral 1 in it is called the BUSY lamp. (If our weapon control system had more than one fire control system, each of them would be represented by a different lamp and number.) The BUSY lamp is lighted whenever the director is assigned the target. The IND lamp is lighted when the director is operating INDependently of the weapon direction equipment. The TRACK lamp indicates that the assigned target is gated and is being tracked. The KILL lamp lights when a target has been destroyed. The observation of the kill is usually visual.

The FCS NON-OP lamp indicates that some part of the fire control systems is not in operation. When missiles are launched, the SALVO-IN-FLIGHT lamp lights. If another salvo is ordered to be fired, the FIRE-AGAIN lamp lights to indicate that this order has been sent to the weapon assignment console, but that the salvo has not yet been fired.

The pushbuttons at the left labelled DESIGNATE FROM, and the pushbutton at the right labelled DESIGNATE TO FCS, are used in making assignments of a director to one of the three tracking channels. The operator makes the assignments by simultaneously pressing the selected "designate from" button and the "designate to FSC" button until both lights function. This process connects the director to the selected tracking channel and slews the director automatically onto the target. At this time the repeat-back symbol, (numeral representing the FCS), moves until it is superimposed on the track channel symbol. This indicates to the director assignment console operator that the system is tracking the proper target.

Weapon Assignment Console

The Weapon Assignment Console is the connecting link between the fire control system and the weapon launcher. It displays data from the fire control system, giving the target's present and predicted intercept positions, and information from the computer indicating whether or not missile intercept is possible. It also has a summary display of launcher information.

The missile firing key is located on the weapon assignment console. Decision of whether or not to fire is made from this station.

The console has a PPI display showing a horizontal plot and true bearing, with own ship's position in the center. Around this plot is a fixed bearing ring. Radial lines from the center to the edge of the plot, generated electronically, indicate launcher unclear areas caused by ship's heading. These lines rotate with changes in ship's heading. This display is similar to the plan plot of the director assignment console.

The other indications on the cathode-ray tube display appear only while the fire control system is tracking a target. These indications are:

1. An "X" indicating target present position
2. A small circle indicating target future position at the predicted point of intercept
3. A large circle about the center, which indicates the maximum range the missile can reach at the target's predicted altitude at intercept
4. A thermometer-type display at the left-hand edge of the plot, giving the target's predicted altitude at intercept (H)

TYPICAL MISSILE FIRE CONTROL SYSTEM

In this section we will discuss the equipments that make up the fire control system of a typical guided missile ship. Look again at figure 5-1. We have assumed that the fire control system shown is capable of controlling gun and missile batteries at the same time. This is a valid assumption, because there are systems with this capability in the fleet. But for now we will separate the capabilities and consider the fire control system a missile system.

In chapter 2, we said that the fundamental fire control problem contains three basic elements—a line of sight, a prediction angle, and a line of fire. The line of sight is established by the radar set of the director. The fire control computer calculates the prediction angle and uses it as an offset to the line of sight to establish the line of fire and to produce weapon orders. The orders are transmitted to the missile launcher to position it in the line of fire.

Thus the primary basic functions of the fire control system are: to acquire and track targets; to develop launcher and missile orders; to guide missiles to the target; and in some instances to detonate the missile's warhead.

Secondary functions of the system are to provide target information such as target speed, target course, range to the target, and system and weapon status information to the display units of the weapon direction system. This information is used to evaluate the tactical situation and to aid in the fire control system and weapon assignment.

The Director or Radar Set

The director or radar set can search for, detect, acquire, and track a target; and it can "capture" and guide a missile. Let's stop and consider the terms "director" and "radar set." A director may contain a radar and/or optics for tracking and ranging, and it is usually manned. A missile director has no optical tracking device or rangefinder but relies on its radar set for tracking. It is not manned in the sense that a man is located inside the antenna supporting structure. True, there is an operator in the radar control room; but his primary function is to monitor the equipment. In the rest of this discussion we will use the term "radar set," rather than director, because that name is more descriptive of the function of a missile director.

The radar set described here, and illustrated in figure 5-1, is an automatic target tracking and missile guidance radar. It normally receives target designation signals from the weapon direction equipment, via the fire control computer. The designation signals position the radar set at the designated range, bearing, and elevation. If the radar set does not acquire the target immediately the fire control computer originates a search program for the radar set to seek out the target. If the ship has more than one fire control system, designation between systems is possible. Designation from another fire control system, called "Interdirector Designation" or "IDD", is accurate and a search program is not needed. Therefore IDD does not go to the computer but through the fire control switchboard to the radar set.

When the radar set acquires the target in range, bearing, and elevation the radar set locks on the target and starts to track it. Tracking circuits within the radar set automatically keep its tracking beam on the target. Target position is continuously transmitted to the computer. The computer and the radar set working together solve for the target's rate of movement about the ship by calculations based on the line of sight movements.

The radar not only tracks the target, but also transmits radar beams to control the missile and guide it to the target. In the case of the beam-rider missile the radar set will transmit simultaneously, on a common nutation axis, three distinct beams—the tracking, capture, and guidance beams. A narrow tracking beam first acquires and tracks the target. The wideangle beam captures the missile after launch, and holds it until it enters the narrow guidance beam that guides it to the target.

Where a semiactive homing missile is used, the radar set will transmit simultaneously, on a common nutation axis, a tracking beam, and an illuminating beam. After the missile is launched it will lock on to the illuminating radar's energy reflected from the target, and home on it. If a missile whose guidance is a combination of beam-rider and semiactive homing is launched, the radar set will transmit a tracking beam and a beam-riding guidance beam and later switch on an illumination beam.

The radar set consists of two major groups of equipment: an antenna group, and a control and power group. The antenna group, which is located abovedeck, consists of a pedestal upon which is mounted the antenna and the necessary electrical and mechanical components required to stabilize and position the antenna. Housed inside the mechanical structure of the antenna group are the transmitting, receiving, and associated microwave circuits. Here, too, are located the gyroscopes that space-stabilize antenna, and thus the radar beams, to compensate for the roll and pitch of the ship. You will study these gyroscopes in chapter 9.

The control and power equipment group is located belowdecks in a compartment usually called the radar room. This room contains the radar consoles used to operate, monitor, and control the radar set. Also located in the radar room are the cabinets containing the power supplies that provide the operating voltages for the various units in the radar set.

Typical Missile Computer

The typical guided missile fire control computer described here is an electromechanical type designed to operate automatically. No operating personnel are needed. It is located in the ship's plotting room, and is used with the radar set described previously.

The computer has three basic ways of operating. It can operate when designation is desired; then, after the radar set has acquired the designated target, the computer aids the radar set in tracking it. As soon as the missiles have destroyed the target, the computer shifts to the air-ready method of operation. These different methods of operating are called modes. The various modes of computer operation can be briefly described as follows.

AIR-READY MODE.—In this mode the computer is energized, but is receiving no information. It generates orders only to put the radar set and launcher in predetermined air-ready positions. For example, the air-ready position of the radar set may be at zero° of train and 45° of elevation; the launcher air-ready position may be at 180° of train and zero° of elevation.

DESIGNATION MODE.—The computer goes into this mode of operation when it receives a "director assigned" signal from the director assignment console of the WDE. The computer directs the radar set to the designated target position so that the radar line of sight will point at the target. It also sends a search program to the radar set. The search program causes the radar beams to move in a preset pattern about the designated target position. The radar searches for the target, and when the target is gated the computer automatically goes into the track mode of operation.

TRACK MODE.—When the radar set acquires the target in range, bearing, and elevation, the track mode starts. The radar set then transmits an on-target signal to the computer. The computer sends signals to the radar set that cause it to drive at a rate that will keep it locked on the target. The computer determines the proper lead angles for the launcher, and transmits these quantities in the form of electrical signals. These signals drive the launcher to the proper aiming position.

Before the missiles are launched, the computer determines and transmits to the missiles quantities that move the missile gyros to their proper positions. The computer also transmits tactical data such as present target position future target position, and missile time to target intercept (time of flight) to the various display consoles of the WDE.

DELIVERY UNITS IN A TYPICAL WEAPONS SYSTEM

The delivery units of a typical weapon system are the gun and the missile launcher. In this section we will discuss only the missile launcher and the equipments associated with it. Guns are covered in Fire Control Fundamentals, NavPers 91900, and Seaman, NavPers 10120.

Guided Missile Launching System

The guided missile launcher shown in figure 5-4 is part of a group of equipments that are known collectively as a Guided Missile Launching System. A guided missile launching system has three major components:

1. Guided missile launcher
2. Guided missile launcher feeder
3. Guided missile launching system control

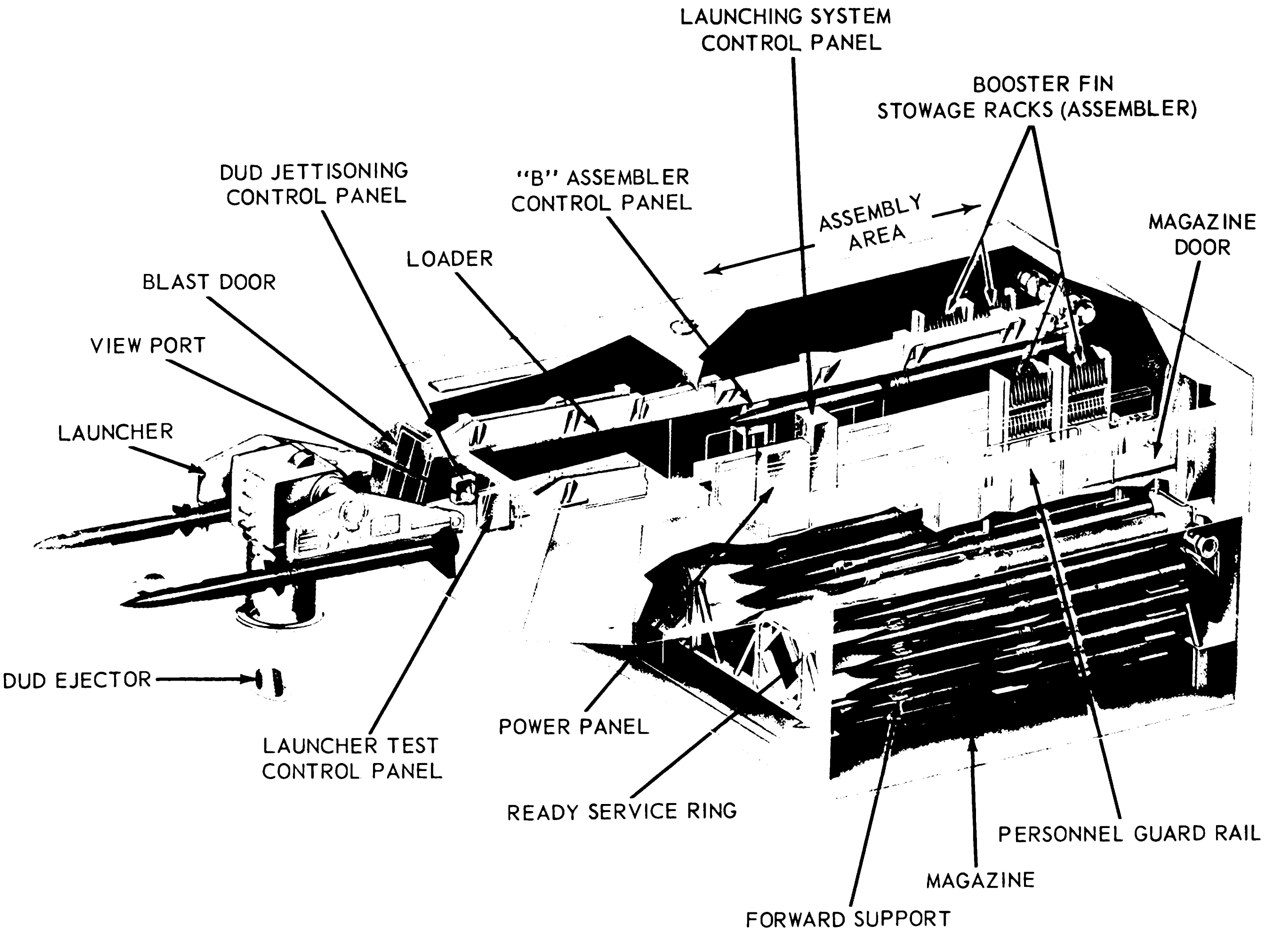
The primary purpose of a guided missile launching system is to stow missiles until needed and then supply them to a launcher for firing. Its secondary function is to remove unfired missiles from the launcher and return them to the missile stowage area.

GUIDED MISSILE LAUNCHER.—Except for Polaris, all Navy missiles that are launched from ships use zero-length launchers. This type has one or two, usually two, launcher arms (or rails). The launcher shown in figure 5-4 is the dual-rail type. It receives and secures two complete missiles—one on each launcher arm. The launcher automatically trains and elevates in response to synchro signals (missile launcher orders) from the fire control computer. Through various devices on the launcher arms, the missiles receive warmup power before launch. Warmup power is used to bring the missile gyros up to speed, and to warm up the vacuum tubes, without taking power from the missile power supplies. Preflight information is also supplied to the weapon through contactors in the launcher arms, and the firing circuit is connected through the launcher to the missile's internal firing circuitry. The launcher can automatically return to a predetermined fixed position in which a new missile can be loaded on the launcher arm, or an unfired missile can be returned to stowage.

LAUNCHER FEEDER.—The purpose of this group of equipments is to stow guided missiles and their boosters in magazines, to remove them from the magazines, and to load them on the launcher arms. There are several types of feeders, but they all have these two purposes. The feeder described here is the most common type. The other systems are similar in operating principles.

The feeder consists of three functional groups of equipment—the magazine, the loader, and the assembler. Figure 5-4 shows the magazine area. The main piece of equipment in the area is the ready-service ring, in which the missile-booster combinations are stowed. The ring can rotate like the magazine of an automatic revolver. This rotating motion of the ring is called "indexing." The ring is indexed to position a missile round so that it can be placed under the loader. The loader provides a means for removing the missile rounds from the ring and ramming them onto the launcher rails. Figure 5-4 shows one loader rail. Usually there are two of them. Continuous grooves in the rails function as tracks to support the booster shoes during ramming operations. The booster shoes are T-shaped and horseshoe-shaped lugs. The rails of the launcher arms are also grooved to receive these lugs. During the loading or unloading operation, the launcher is positioned so that the loader rail and launcher rail form one continuous track. Missiles are rammed onto or off of the launcher by a rammer chain that is guided by a track in the loader rail. A hook, or pawl, attached to the chain, engages the rear shoe of the booster.

The third group of equipments that make up the feeder is called the assembler. The assembler is essentially a set of racks for stowage of the aerodynamic surfaces (booster fins and missile wings). The wings and fins are mounted on


LAUNCHING SYSTEM CONTROL PANEL
BOOSTER FIN STOWAGE RACKS (ASSEMBLER)
DUD JETTISONING CONTROL PANEL
"B" ASSEMBLER CONTROL PANEL
ASSEMBLY AREA
MAGAZINE DOOR
LOADER
BLAST DOOR
VIEW PORT
LAUNCHER
DUD EJECTOR
LAUNCHER TEST CONTROL PANEL
POWER PANEL
READY SERVICE RING
PERSONNEL GUARD RAIL
MAGAZINE
FORWARD SUPPORT

12.44

Figure 5-4.—Typical Terrier missile launching system.

the booster and missile manually, by men assigned to perform this operation.

LAUNCHING SYSTEM CONTROL.—This equipment group includes the panels used to operate the missile launching system. The power panels contain circuit breakers, overload relays, and other electrical components required by the various power drives that control the movement of the launcher, rammer, and ready-service ring. Other panels contain operating controls that are used to start the system and control its operation. These panels normally respond to orders from the WDE. For example, the WDE may send an order to ALERT the missile launching system. An ALERT light on a panel flashes, indicating to the operator that WDE wants the missile launching system's equipment put into operation. Several of the orders transmitted from the WDE to the missile launching system are of interest to the FT.

TYPES OF ORDERS.—The MISSILE SELECT order is transmitted from the WDE to the launching system to indicate the type of missile to be loaded on the launcher. There are several types of Terrier missiles. All of these types may be loaded together in a single magazine. This is called mixed loading. When the launching system has selected the type of missiles called for by the WDE, it sends back a signal indicating that the order has been carried out.

The LOAD ORDER tells the launching system to start loading a missile or missiles. A load order may be "continuous," "single," or "hold." A "continuous" order causes missiles to be continuously supplied to the launcher. This operation is similar to "rapid or continuous fire" in conventional gunnery. The "single" order causes one missile per arm to be loaded on the launcher. The "hold" order holds the launching system in a ready-to-load condition.

When the launching system receives the UNLOAD ORDER, it unloads any missiles that may be left on the launcher arms.

The INTENT-TO-LAUNCH (ITL) is similar to the conventional "commence fire" order in one respect—it is transmitted by closing a firing key. But, while the gun firing circuit is completed almost instantly when the key is closed, there is a slight delay before a missile firing circuit is completed. This delay is necessary to establish certain operating conditions in the missile, and other equipments in the weapon system. Before the missile can be fired, it must indicate that it is ready to be launched. This indication, "missile-ready-to-fire," is sent through the launching system control circuits back to the WDE. Almost every piece of equipment in the weapon system affects the operation of the firing circuit, either directly or indirectly.

DESTRUCTION UNITS IN A TYPICAL WEAPONS SYSTEM

As we mentioned earlier in this chapter, our typical weapons system is designed to control two weapons, the gun (projectile) and a guided missile. Both of these weapons have already been discussed; therefore these units will not be covered here.

GUN FIRE CONTROL SYSTEM

Representative gun fire control systems (GFCS), were discussed in chapter 2. Here we will compare the functions of the major units in a GFCS with those in a missile fire control system, (MFCS). Since the same basic elements are present in the missile and the gun fire control problem, both types of systems will have the same major units and the primary function of the units will be the same. This is clearly illustrated by the fact that the weapon control system we just discussed can control both missile and gun batteries.

Variations between the problems and the functions of the major units are the result of the differences between the guided missile and the gun projectile. The missile is guided during its flight; hence its control problem continues after launch. On the other hand, once a gun projectile is fired the gun control problem for that round is completed. The missile, having a longer range and higher altitude capability, extends the limits of its problem beyond those of the gun problem; but this fact does not change the basic problem.

We will follow target information through a gun fire control system, starting with the initial detection of a target by the search radar. At each major unit we will point out the principal differences between it and its counterpart in a missile system.

TARGET DESIGNATION SYSTEM

The target designation system (TDS) is the connecting link between the search radar and the GFCS. The function of the search radar is the same as it is on a missile ship. Due to the limitations of the guns, particularly their range limitation, the designation equipment for a gun battery is simpler than the WDE for a missile battery. A single console with a PPI presentation is used to evaluate, track, assign, and designate targets to the GFCSs.

Guns are assigned to a GFCS by a prearranged ship's doctrine. Thus when the TDS assigns a GFCS to a target, the assignment includes the guns. Normal procedure is to commence fire as soon as the target is within effective gun range. The firing circuit is controlled within the GFCS. Thus when the director has acquired the target, the TDS has completed its job with respect to this target and GFCS.

A gun can be fired relatively fast compared to launching a missile. No warmup time is necessary; as soon as the gun is loaded it can be fired. A gun is "quick on the draw" so to speak, and can be used effectively against short-range targets picked up optically. The TARGET DESIGNATION TRANSMITTER, an optical target detector, can transmit target designation directly to the GFCS without going through the TDS.

If more than one FCS is installed, designation can normally be made between the systems. As you know, this method of target designation is called IDD (interdirector designation).

GUN DIRECTOR AND COMPUTER

Gun directors are manned, and normally have both optical and radar equipment to detect, locate, and track a target. The director crew can readily shift from optical to radar tracking, or vice versa. The radar transmits a single target-tracking beam. Another function of gun directors is to furnish a centralized control station and a remote firing station for the battery.

There is little to distinguish between gun and missile computers. Due to the nature of today's air targets, AA computers are almost fully automatic, with little or no provision for manual operation. Gun computer outputs of train, elevation, fuze, and parallax orders drive the gun to the predicted position of the line of fire. The entire problem of locating the correct line of fire is solved before the projectile is fired.

WEAPON SYSTEM FUNCTIONING

To provide a brief review of what you have studied so far in this chapter, we list the principal steps or phases a typical weapons system goes through to accomplish its mission. The mission, of course, is to destroy the enemy or a practice target. The principal steps, in chronological order, are:

1. TARGET DETECTION. Search radars detect targets at long ranges, to allow time for the weapons system to go into action and complete its function.
2. TARGET SELECTION. The weapons direction system selects the targets that appear hostile, and that require missile and/or projectile interception, and inserts them into tracking channels. Target selection and tracking is performed by personnel assigned to the target selection and tracking console—a unit of the weapon direction equipment.
3. SEARCH RADAR TARGET TRACKING. The tracking channels (computing circuits) continuously track selected search radar targets to generate target rate of movement. This data appears as a symbol (letter) on the face of a large cathode-ray tube (scope). When the tracking channel has computed the correct target course, speed, and rate, the symbol on the scope will remain superimposed on the target echo supplied by the search radar. This computed target position and rate data is used for evaluation of the tactical situation presented to the ship, and for transmission to other units in the WDS—especially the director assignment console. Each target that is being tracked is assigned a different symbol to prevent confusion.
4. EVALUATION. The weapon system evaluates the threat of various targets, decides which should be engaged by guns and which by missiles, and decides which targets should be given priority. The evaluation is performed by personnel, but they are aided in this process by the displayed information on the various consoles in the WDE and CIC.
5. DIRECTOR ASSIGNMENT. A radar set is assigned to the target having the highest priority. When a radar set is assigned, this implies that a fire control system has been included in the assignment.
6. ACQUISITION. The assigned radar set (fire control system) gets on the target.
7. TRACKING. The fire control radar tracks the target to provide precise target position and rate data. The computer associated with the tracking radar operates on the data from the radar set to provide the solution to the fire control problem. The computer answers are supplied to the guns and launcher as synchro signals to position these units in train and elevation.
8. REEVALUATION AND WEAPON ASSIGNMENT. The target that is engaged by the fire control system is reevaluated with respect to the tactical situation (this may have changed), availability of the launcher or gun, and the range limitations of the weapons.
9. LOADING. Missiles are loaded on the launcher, and the guns are prepared for firing.
10. LAUNCHING AND FIRING. The missiles are launched at the proper time and in the proper direction. The guns are loaded and fired.
11. MISSILE GUIDANCE. The fire control radar guides each missile to the target being tracked. Gun projectiles, of course, receive no guidance.
12. TERMINAL PHASE. When a missile or projectile approaches to within lethal range of the target, a VT fuze detonates its destructive charges. This is the "moment of truth" for the weapons system.

CHAPTER 6

BASIC MECHANICAL AND ELECTRICAL COMPONENTS

As its name tells you, this chapter is concerned with the mechanical and electrical components serviced by Fire Control Technicians. All of the fire control equipment that you will be associated with contains one or more of the units discussed in this chapter. The material presented here is dependent upon Basic Machines, NavPers 10624-A and Basic Electricity, NavPers 10086-A for the principles applicable to those components.

This chapter is divided into two sections. In the first section we shall consider the more common mechanical components and in the second section the basic electrical components.

MECHANICAL COMPONENTS

SHAFTS

Shafts provide a mechanical means of transmitting motion between units. There are two basic types of motion: angular (rotary), and linear (translatory). Shafts can transmit either type of motion. A moving shaft can transfer energy from one point to another. For example, in a motor-generator set the power motor is coupled to the generator by a shaft. The torque produced in the motor is transmitted to the generator to rotate it at a definite speed. Of prime importance in this application is the number of shaft revolutions per unit of time. In this application the angular position of the shaft has no practical value. A shaft, however, can also transmit angular data.

The first things you see when you look inside a mechanical computer are many shafts and gears. And they're all there for specific purposes: to couple computing devices, to connect computing units, to drive and to position the dials. Equally important, external shafts and gears connect fire control instruments—as the stable element with the computer, the director with its radar antenna, and the gun with its sights.

Small electric followup motors transmit motion to the various computing devices through shafts. You'll find that a computer contains several of these motors. However, a single motor may position several devices at different places in the machine.

The angular positions of the shafts that couple these computing devices represent actual quantities—degrees of an angle or yards of range. The amount of change in the transmitted quantity represented by one revolution of a shaft is called shaft value. The total value carried by a shaft is the shaft value multiplied by the number of revolutions made by the shaft from its zero or reference point. For example, the shaft value for bearing data in an instrument might be 10° per revolution. If the shaft made six and a half revolutions from its zero position, bearing in the instrument would be 65°. Shaft value is a designed feature and can be made to represent any reasonable value. Generally speaking, however, accuracy decreases with an increase in shaft value. Shaft value is the ratio between shaft motion and the change in value of the quantity being transmitted. Later in this course we will discuss scale factor in a computer. The two terms have similar meanings.

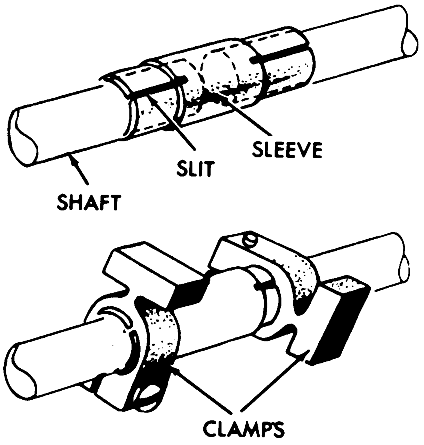
The accuracy with which a shaft can be positioned depends in part on the resistance to shaft motion. In many installations the power available is limited. This is particularly true in fire control computers where space and weight are critical commodities. Moreover, in servosystems the power output is directly related to the error size. Thus as the shaft approaches the correct position the power is reduced. Friction between moving parts must be held to a minimum. Shafts are mounted in ball bearings and carefully machined parts to reduce friction and to ensure as near perfect rotational alignment as possible. Misalignment between the rotational axes of a shaft line and its associated components will cause eccentric rotation which, among other things, will increase the resistance to motion.

Coupling Devices

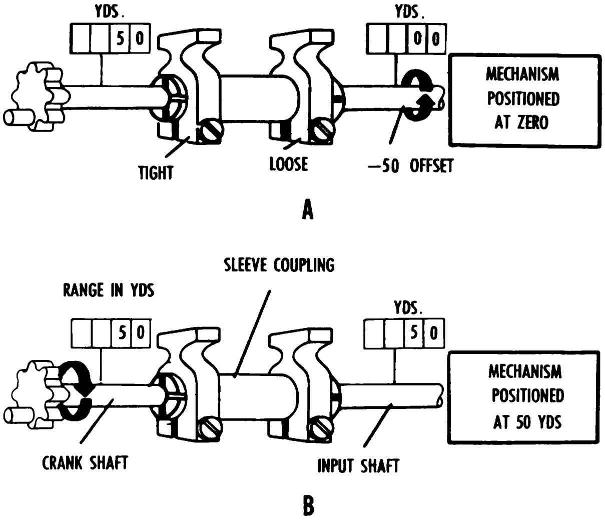
Coupling devices are used to mechanically connect shafts together to form a shaft line or gear train. Coupling devices are covered in Basic Machines, NavPers 10624-A. Therefore, our discussion here will be limited to their application in fire control equipment. As a connecting link between shafts, they provide a means to compensate for the misalignment between the axes of rotation of the shafts, and for end play in the shaft line. They also make it possible to adjust the rotational angle between the shafts. Couplings used in fire control equipment to connect shafts end-to-end are: the sleeve, the Oldham, the flexible, the universal joint, and the quick disconnect.

Figure 6-1 shows the sleeve coupling. It is used to join two shafts that lie in the same straight line; that is, shafts that are very closely aligned. It consists of a simple metal tube or sleeve, slit at each end. The slitted ends enable the clamps to fasten the sleeve securely to the shaft ends. When the clamps are tight, the shafts are held firmly together and turn as one shaft. They serve as a convenient device for making adjustments between units.

Figure 6-2 shows a mechanism which receives range, via a shaft, from a handcrank.



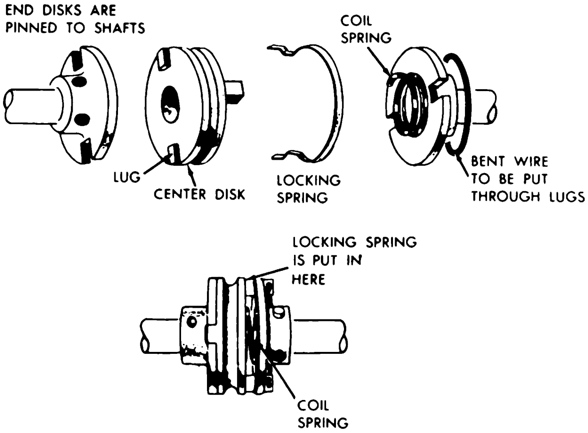
12.51
Figure 6-1.—Sleeve coupling.



110.11
Figure 6-2.—A coupling used to adjust a shaft line.

In part A of the figure, the range indicated in the mechanism does not correspond with that introduced by the handcrank; there is a 50 yard offset. This condition can be corrected by loosening the sleeve coupling, rotating the mechanism shaft until the two range values agree, as in part 3 of the figure, and then retightening the coupling.

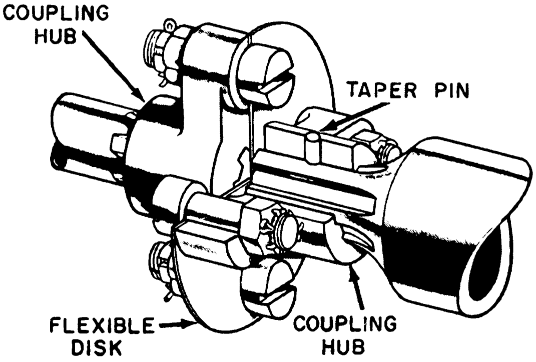
The Oldham coupling, named for its inventor, is used to eliminate the need for perfect alignment between shafts. At the same time, it affords a convenient means for decoupling the shafts quickly. You can see this coupling in figure 6-3.


END DISKS ARE PINNED TO SHAFTS
COIL SPRING
LUG
CENTER DISK
LOCKING SPRING
BENT WIRE TO BE PUT THROUGH LUGS
LOCKING SPRING IS PUT IN HERE
COIL SPRING

12.52
Figure 6-3.—Oldham coupling.

The Oldham coupling has another use. As you know, metals expand and contract with changes in temperature. With long shafts, this effect could cause trouble. The Oldham coupling compensates for this as the coil spring absorbs the changes in shaft lengths.

The flexible coupling shown in figure 6-4 connects two shafts by means of a metal disk. The coupling hubs are splined to the two shafts and are bolted to the metal disk. The flexible coupling can compensate for a slight misalignment of the shafts.



84.133.2
Figure 6-4.—Flexible coupling.

A shaft line or gear train is usually put together in such a way as to turn corners to get around units, and so on. This requires the rotational axes of connecting shafts to intersect at an angle, rather than in a straight line. The universal joint (fig. 6-5A) is used to connect shafts that intersect at angles up to 25°.

The quick-disconnect coupling (fig. 6-5B) is used where it is often necessary to remove a subassembly. The male or pinned shaft fits into the open slots of the sleeve. The sleeve is kept from slipping by a pin through the shaft and the closed slot in the sleeve. A spring holds the sleeve in place. To disconnect the shafts, the sleeve is merely pushed back against the spring pressure.

Gears

The devices most often used to couple shafts together are gears. Gears may also be used to change the angle of a shaft line's rotation (fig. 6-6); to reverse the shaft line's rotary motion (fig. 6-7); to increase or decrease the speed of rotation and thus change the amount of rotation and the mechanical advantage of the shaft line (fig. 6-7); to make a shaft line unidirectional, that is irreversible (fig. 6-8); and, finally, to convert one type of motion, (linear, angular, etc.) to another. See figure 6-9. As you can see, a gear is a very versatile basic mechanism. Gears are covered in Basic Machines, NavPers 10624-A. Be sure you understand the applications of each type of gear and the principles of gear ratio. You will need this information in your study of many kinds of fire control equipment.

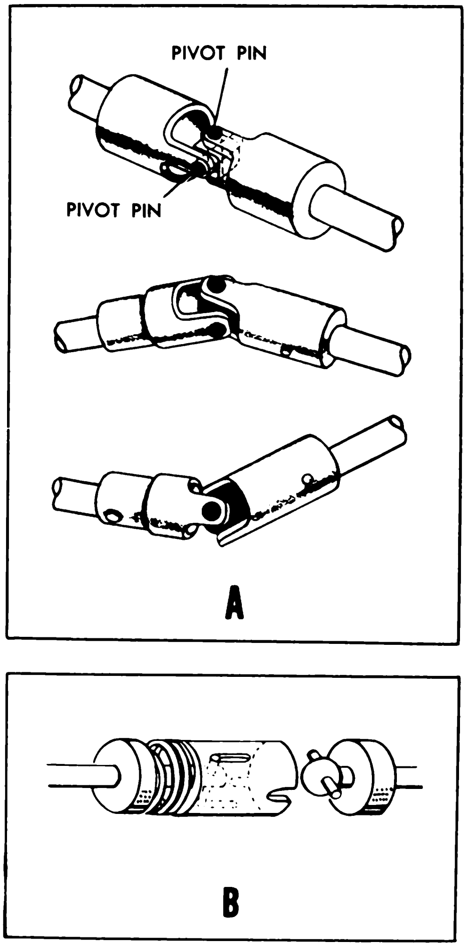
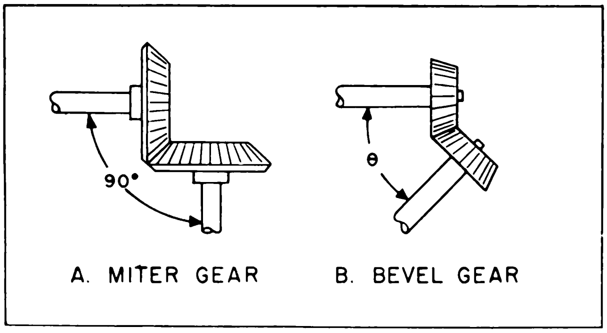


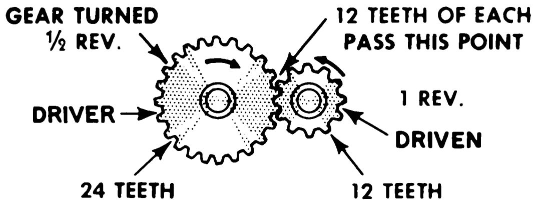
Figure 6-5.—A Universal joint; B. Quick-disconnect. 5.34A

Lost Motion

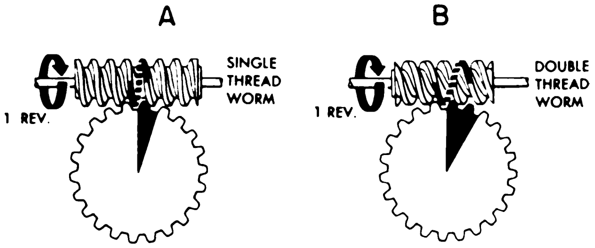
The tolerance for errors in fire control equipment is very small. Since many of the shaft lines carry angular data which must be accurate to the nearest minute of arc, it is



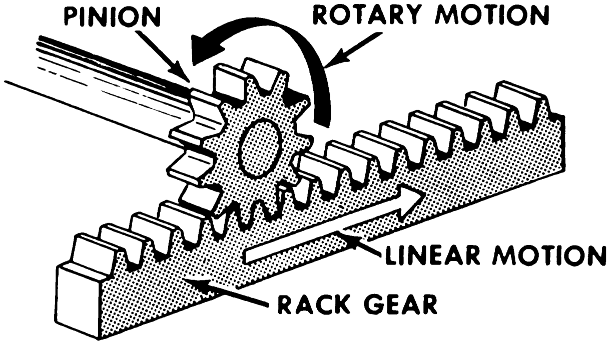
5.22:.24
Figure 6-6.—Angular change of shaft line axis.



12.57.1
Figure 6-7.—Gear ratio.



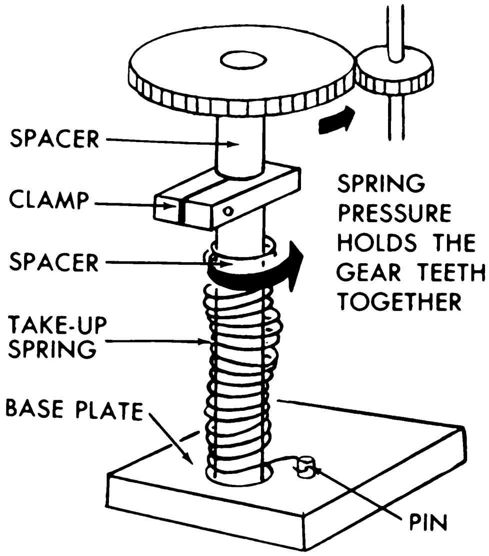
5.22.9
Figure 6-8.—Irreversible shaft line.



5.22.13
Figure 6-9.—Angular to linear motion.

important that the gears fit accurately and with a minimum of lost motion. A mechanical device, in order to move, must have room to move. Consequently, a small amount of space is necessary between mating mechanical components, such as gears, to allow them to move. This space results in lost motion. Lost motion is the distance the driver gear turns before the driven gear begins to turn. This distance is called dead space. The total lost motion in a gear train is the sum of the lost motion in each gear mesh. Lost motion adds up to a considerable error on a long shaft line with many gear meshes.

LOST MOTION TAKEUP SPRING.—Once a shaft line is turned, all the dead space between the gears is removed in the direction of rotation. With the dead space gone, there is no more lost motion in this direction. A lost motion takeup spring removes the dead space by holding the driving gear teeth firmly against one side of the driven gear teeth (fig. 6-10). The takeup spring is attached at one end to the mounting plate and at the other end to a clamp on the shaft. The clamp is held in place by



12.265
Figure 6-10.—Lost motion take-up spring.

spacers on the shaft. Spring pressure applies a torque to the driving gear both while the shafts are turning and while they are stationary.

Classes of Gear Fits

The dead space obviously reduces the accuracy of data transmitted by a gear train. In power transmission systems, the dead space will cause backlash in the drive. Backlash results in a jarring or jerky reaction to sudden movements, or to a reversal of the motion. This is a particularly serious problem where the load has a large amount of inertia due to its weight or velocity.

The degree of accuracy required of a gear train varies for different applications. In computers, the gears are meshed or fitted very closely to reduce lost motion. In other applications a specified clearance between the driver and driven gears' tooth surface is allowed. We will list a representative group of classes of gear fits used in the assembly of a fire control instrument. The clearances for the different classes represent a compromise between accuracy and other operational characteristics.

A CLOSE FIT has a very high percentage of the driver and driven gear's tooth surface in actual contact. This fit is used in computing instruments because it has a minimum of lost motion. Gears so fitted should turn smoothly, but may require an additional torque due to the friction caused by the large area of contact. The mesh between gears in this class of fit is critical. If the gears are meshed too closely, the line will jam. A loose mesh, on the other hand, will introduce lost motion.

A RUNNING FIT has some dead space. There is a clearance between adjacent surfaces of approximately .001'' to .002''. In a gear mesh, the stated clearance is equal to half the lost motion which may be accumulated by loading the gear.

A CLOSE RUNNING FIT is midway between a close fit and a running fit. This is the normal fit used in the assembly of fire control instruments unless another class is specified.

A FREE FIT has a clearance of approximately .003'' to .005'' between mating tooth surfaces. This fit is not critical, and can be determined by "feel."

A FREE RUNNING FIT is midway between a running fit and a free fit. It has approximately .002'' to .003'' clearance between surfaces.

SAFETY DEVICES

Safety devices are used on shaft lines to protect the mechanisms that the lines connect. Functionally, a shaft line transmits motion, and the amount a shaft line can rotate by itself is limitless. Moreover, the torque a shaft line can transmit is normally much greater than the torque limit of the mechanisms it connects. The safety devices limit the amount of rotation or the torque of a shaft line. There are many variations to the three representative types of safety devices we will discuss. The principles of operation of all the devices in each type, however, are fundamentally identical.

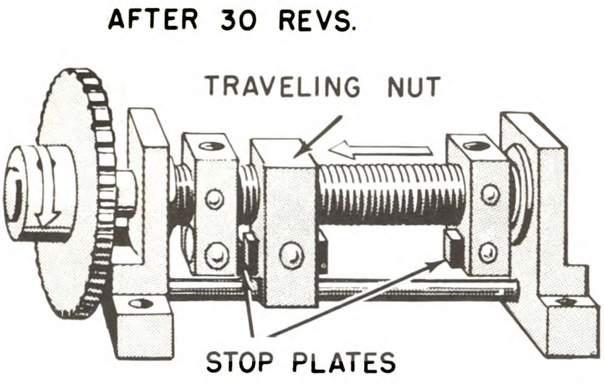
Limit Stops

Limit stops are mechanical safety devices for arresting or limiting motion. They are usually used to prevent shafts from rotating farther than they should. They are often used to keep handcranks or electric motors from driving past the limits of the mechanism to which they are connected. There are two general classes of stops. One limits the shaft motion to 360 degrees or less, and the other limits the shaft to a certain number of revolutions.

The first type consists of three metal blocks, with inserted steel stop plates. Two of the blocks are fastened to the framework of the machinery close to the shaft that is to be limited. The third block is pinned to the shaft. For instance, if the blocks are set to limit the rotation to 180 degrees, then every time the shaft makes a half turn in either direction, the stop plate on the rotating block touches the stop plate on one of the fixed blocks. This prevents the shaft from rotating farther. The fixed blocks can be set to limit shaft rotation to any predetermined value. If one fixed limit stop is removed, the shaft will rotate almost 360 degrees.

The second type, as shown in figure 6-11, is the type most often encountered. This limit stop consists of a traveling nut on a threaded screw, a guide rod to prevent the traveling nut from rotating, and two adjusting nuts. The adjusting nuts are pinned to the shaft on either side of the traveling nut, and turn with the shaft. The shaft is stopped from turning when the stop plate on one of the adjusting nuts hits against a stop plate on the traveling nut.

The distance between the adjusting nuts is accurately set, before the stop is installed in the machine, to correspond with the exact number of revolutions the shaft can make before it must

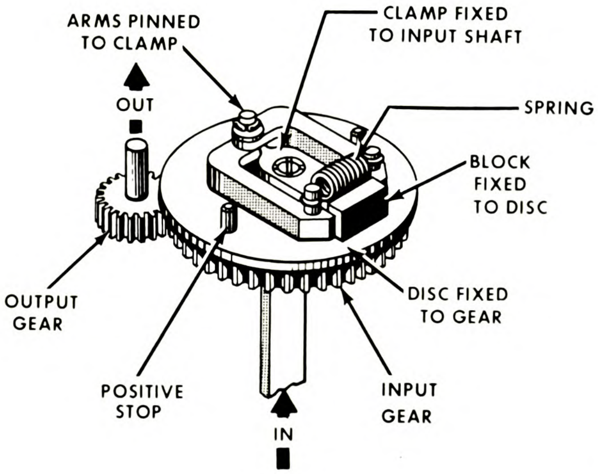


12.266
Figure 6-11.—Limit stops.

be stopped. For example, a line is to be limited to 30 revolutions from its zero position. When the line is at zero the traveling nut will be against one of the adjusting nuts. After 30 revolutions of the line, the traveling nut will have traveled to the other adjusting nut, and the shaft will not be able to turn any farther.

The Shock Absorber

The shock absorber used in a computer is really just a special type of coupling. It has provisions for absorbing shock which distinguish it from other couplings. Briefly, it consists of a clamp coupled to a gear by a spring and arm arrangement. The clamp fastens the shaft to the hub of the gear. You can see this in figure 6-12.



12.59
Figure 6-12.—Shock absorber.

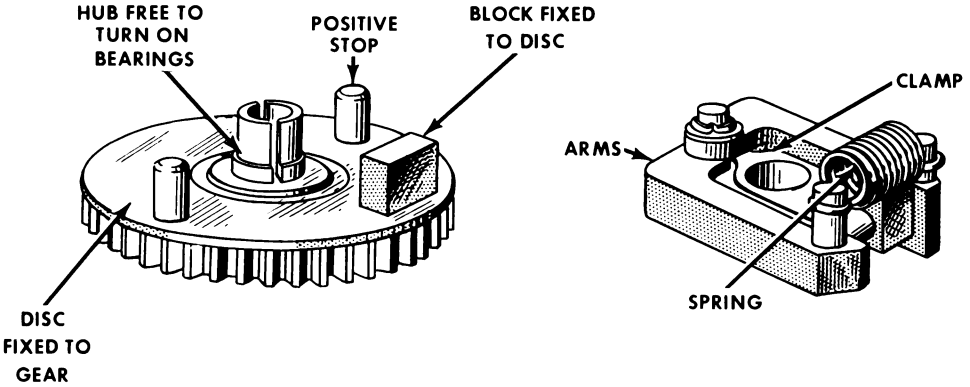
Follow the action in figure 6-12. To start with, the input shaft turns the input-gear hub clamp. The arm ends push the block, which is fixed to the disc that is fixed to the input gear. In turn, the input gear drives the output gear and output shaft. The thing to visualize is that the arms give against the spring to absorb the shock when the input shaft is started suddenly. That's the trick to the whole works.

Take a look at the disassembled view of the shock absorber in figure 6-13. It shows you exactly how it is constructed. There are two important things to see in the figure. First, note that the hub is free to rotate in the gear and is mounted on ball bearings. And second, note that the clamp fastens the hub to the input shaft. Then, when the clamp is attached to the hub, the arms are stretched against the spring to sandwich the block on the disc. The two positive stops simply stop the arms to keep the spring from overstretching.

Friction Relief Drive

A friction relief drive is a special shaft line coupling which will slip when the torque on the line is too great. This device protects the gearing and mechanisms on the line from damage from an excessive amount of torque. The construction of a typical friction relief drive is shown in figure 6-14. The gear is free to turn on the input shaft. Friction disks are cemented to both sides of the gear. The flanged hub is pinned to the shaft and rotates with it. The hub is in contact with the friction disk on top of the gear. The sliding flange is connected by a tongue and groove arrangement to the collar which is pinned to the shaft. The sliding flange is pressed against the bottom friction disk on the gear by spring pressure. Hence the gear is sandwiched between the two flanges by spring pressure. The compression of the spring may be adjusted by the clamp which can be screwed on the threaded sleeve when the clamp is loose. The output of the drive is taken from the gear.

The connection between the input shaft and the output gear of the drive is the friction coupling between the flanges and the gear. The friction is adjusted so that under normal conditions the gear will turn with the shaft. But if the torque is greater than normal, or if there is a restriction on the line, the friction drive will slip before any damage is done. For example, a shaft line with a limit stop which is at one of its limits is mechanically restrained



12.60

Figure 6-13.—Shock absorber, disassembled view.

at that value. An attempt to force the line beyond the limit could damage the mechanisms. But a friction relief drive in the line will allow the motion to slip and relieve the torque on the line.

HANDCRANKS

Not all inputs to a computer or rangekeeper are automatic. For instance, the wind values are cranked in by hand. Also, INITIAL ESTIMATES of such quantities as range, target course, and target speed are cranked in by hand to expedite the solution. In fact, some rangekeepers solve the whole fire control problem from inputs cranked in manually. Corrections to these input quantities are cranked in from time to time as the problem progresses.

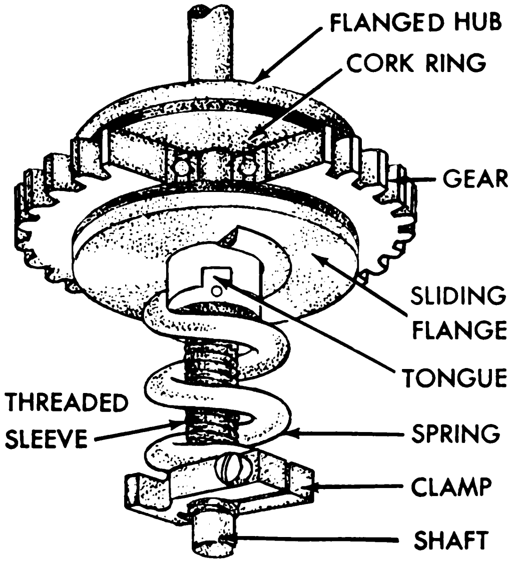
There are several types of handcranks—some simple and some complex. The simple ones are merely used to crank in a quantity, whereas the more complex handcranks may have holding frictions, a selector switch, or a locking device built in to serve several other purposes. But regardless of how many accessories the crank may have, it's still the simple crank built up.

The most simple crank consists of a shaft with a knob pinned to one end and a gear pinned to the other. Then a housing-like adapter is fitted around the shaft with some way of securing the whole assembly to a side or top of the computer.

In order to get a picture of the simple crank built up, look at figure 6-15. This crank has features in common with the several types of cranks you'll be working with. Take the four main features, one at a time, and study them.

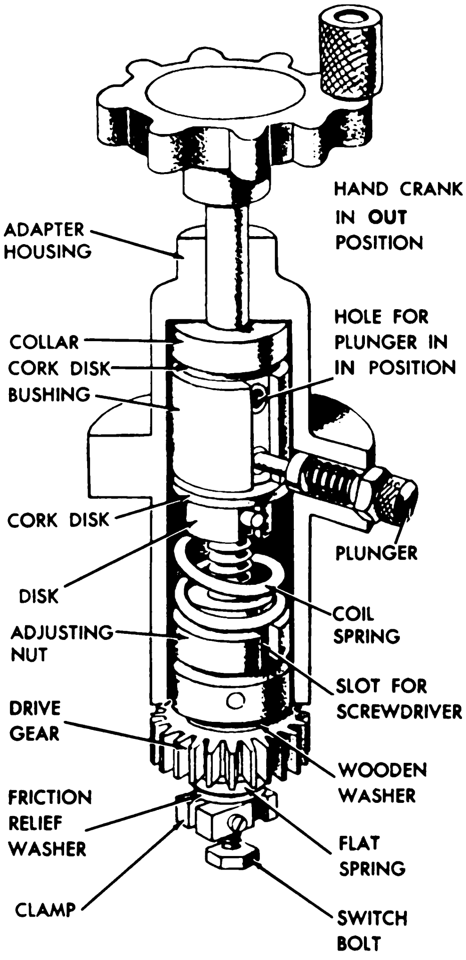
First, the crank has a holding friction created by the pressure exerted against two cork discs by a collar, a bushing, and a metal disc. You can locate these parts in the upper part of the drawing in figure 6-15. Notice that the coil spring furnishes the pressure.

These holding frictions keep the handcrank positioned, and prevent motion from backing out through the handcrank.



12.267

Figure 6-14.—Friction relief drive.



12.62

Figure 6-15.—Handcrank.

Second, consider the friction relief drive. The drive gear is held to the shaft by the friction relief drive consisting of a flat spring, a wooden washer, and a clamp. If the line hits the end of a limit stop, or if the torque on the line is too great, the drive will slip so that the mechanisms and gears within the machine will not be damaged. You can see these parts at the lower end of the crank.

The third feature is the plunger for changing the position of the shaft. The crank in figure 6-15 has two positions—the IN-POSITION and the OUT-POSITION. In changing position, the shaft and drive gear move in relation to the adapter housing. The plunger is used to hold the shaft and knob in either of these two positions. The plunger is pulled out and the crank is pushed or pulled to its new position. Then the plunger is returned by its spring when released.

Be sure you get these in- and out-positions straight. Actually, this crank is built to take the place of TWO simple cranks (fig. 6-16). In the in-position, the drive gear is meshed with one gear to crank in a certain quantity; and in the out-position, the drive gear is meshed with another gear to crank in a distinctly different quantity.

The fourth feature is the adjustable switch bolt. This bolt is used to open and close a switch, usually to control an electric motor. It is adjusted to operate the switch at exactly the right time, when the knob is changed from one position to the other.

If you know the crank assembly in figure 6-16, you'll have no trouble with cranks. Remember that the crank can be used to crank in two quantities (one for each position), and it can operate a switch.

Don't underestimate the importance of these basic mechanical units. Although they may seem simple, they're subject to wear and tear. That means you'll be replacing them from time to time, or filing off burred edges, or just cleaning and lubricating their working parts. These basic units are used in the assembly of complex fire control computing mechanisms, which you'll learn about in another chapter. For more information on basic mechanical units, consult Basic Fire Control Mechanisms, OP 1140.

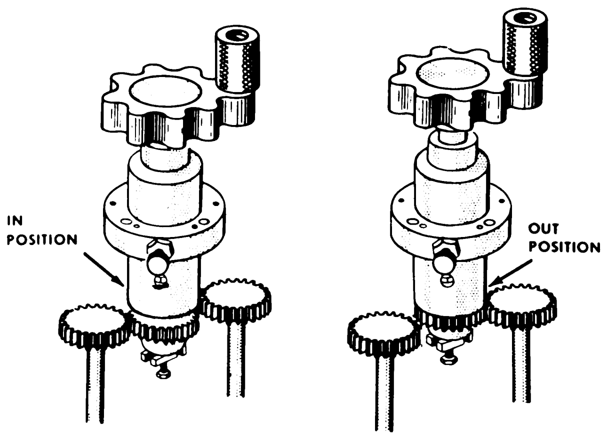
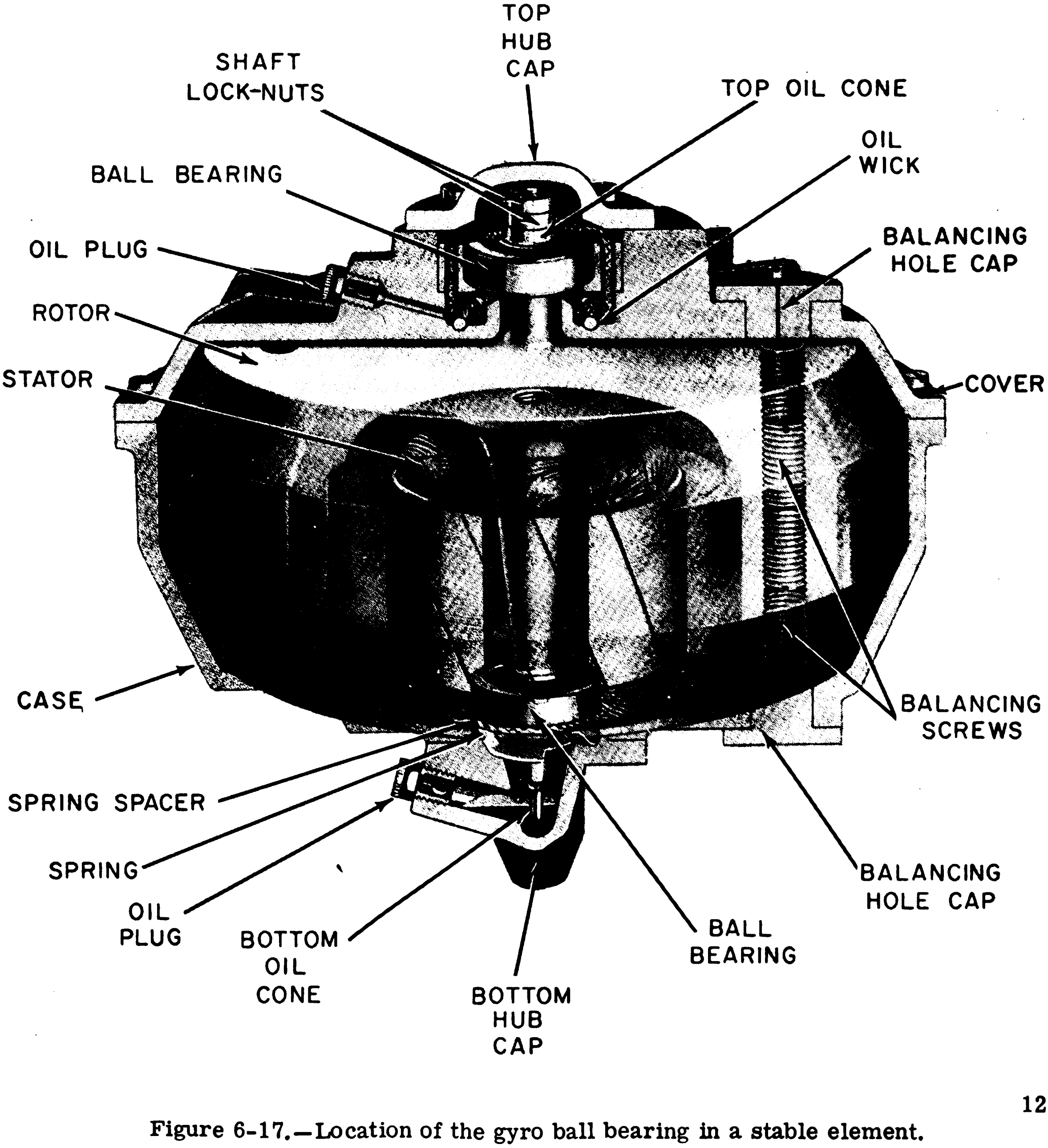


Figure 6-16.—In- and out-positions of a handcrank. 12.63

BEARINGS IN FIRE CONTROL EQUIPMENT

You learned about the various types of bearings when you studied the Basic Machines text. Therefore we will limit our discussion to applications, and to special bearings found in fire control equipment. Mechanical components in fire control equipment are machined to close tolerances. The accuracy of an entire fire control system is often dependent upon the accuracy of a single bearing.

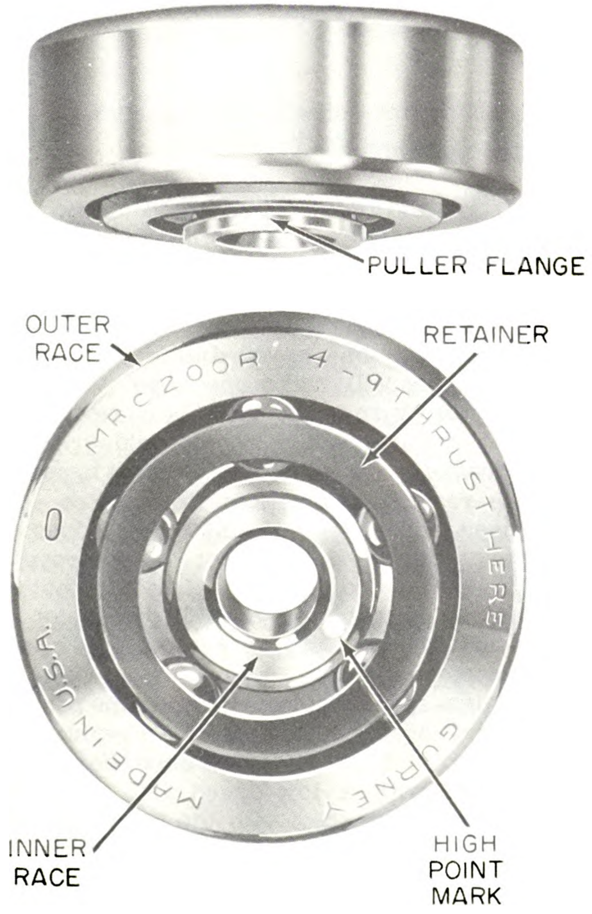


12.268

Figure 6-17.—Location of the gyro ball bearing in a stable element.

Gyro Bearings

A gyro is an inertial weight which is rotated at high speed. The gyro in the stable element, for example, rotates at a speed of approximately 8,700 rpm. The plane of rotation of the gyro is used to establish the reference planes in which the fire control problem is solved. The dynamic balance of a gyro in its plane of rotation is determined in part by its bearing mountings. As in all cases, the type of bearing used is dependent upon the magnitude and the direction of the load upon the bearing and the relative speed between bearing surfaces. Very little axial play and practically zero radial play are allowed in gyro bearings. Only bearings with less than 0.0001" overall eccentricity are acceptable for use as gyro bearings in the stable element (fig. 6-17).



12.269

Figure 6-18.—Gyro ball bearing.

Ordinarily two bearings, a thrust bearing and a radial bearing, would be used to mount the gyro. But a special bearing called a radial thrust bearing may be used. This bearing (fig. 6-18), is capable of carrying a combination of thrust and radial loads. The faces of the bearing's collars carry the thrust load, and its cylindrical surfaces handle the radial load. The resultant of the two loads has an angular component.

The bearings are marked for correct installations. The words "thrust here" scribed on the bearings indicate the side which will sustain a thrust load. The high-point, or point of greatest run-out (eccentricity), is indicated by a dot marked on the bearing. The bearing is installed in a prescribed manner which deals with both these factors.

Roller Path Bearings

A director or radar antenna mount carriage is supported by roller bearings on a foundation which is welded to the ship's structure (fig. 6-19). The carriage is the basic structural frame which supports the rotating equipment in the director. The roller bearings shown in figure 6-20 are between the carriage and the foundation. The horizontal rollers support the

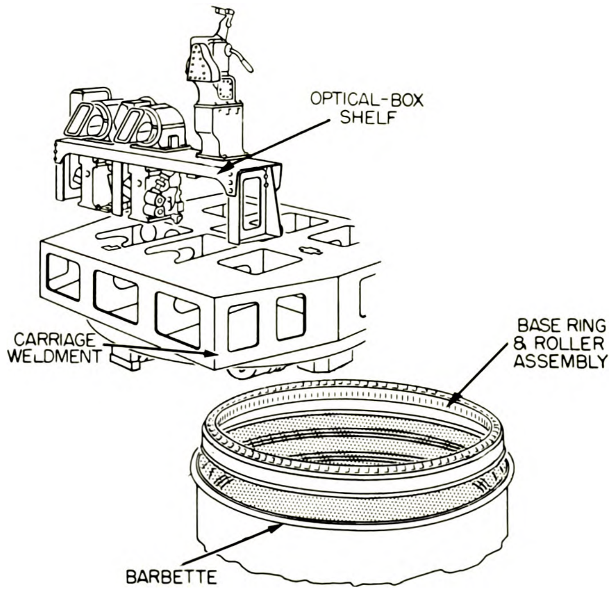


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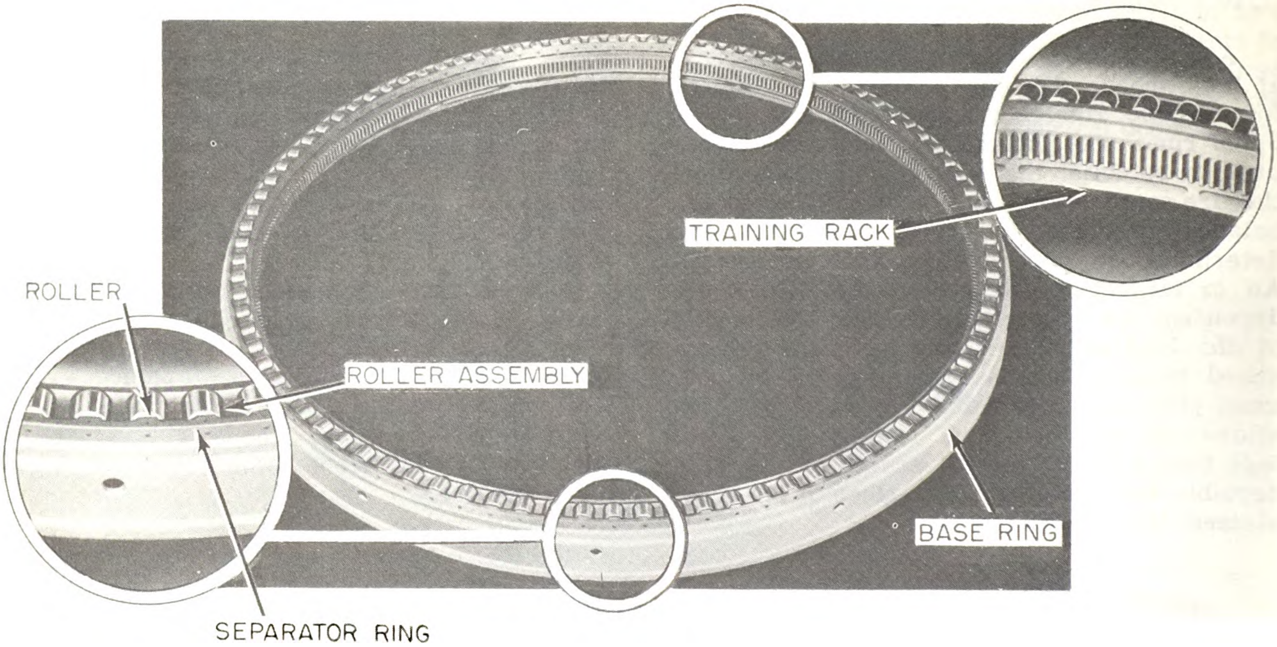
Figure 6-19.—Director foundation and carriage.



12.271

Figure 6-20.—Base ring and roller assembly.

weight (main thrust) of the director. The upper race of the bearing is part of the carriage, while the lower race (which is a highly machined roller path), is part of the foundation. The separator keeps the roller bearings from getting canted and running into one another.

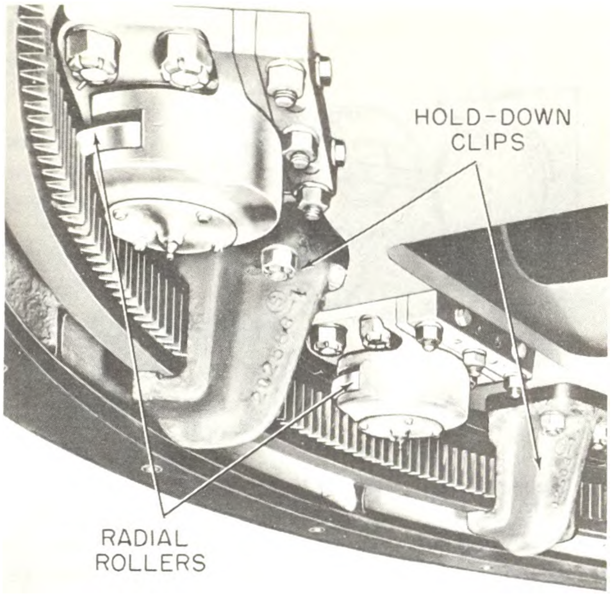
The radial rollers (vertical) prevent side play of the director. The radial rollers (fig. 6-21) are mounted on the carriage and roll on a machined path attached to the foundation. The radial rollers keep the movement of the director concentric with the foundation. The holding-down clips shown in the figure hold the director carriage to the foundation.

COUNTERS AND DIALS

Counters and dials are installed to measure the rotation of shafts and indicate the value of the quantity being transmitted by the shaft. Fire control quantities are represented in mechanical equipment by shaft value and total shaft value. To set-in or read-out a quantity in a mechanical instrument, you must have some means of measuring the position of the shaft with respect to a reference. The reference position of the shaft usually represents the zero value of the quantity being transmitted.

Shaft angles are often indicated on two different dials. One is called the low-speed or coarse dial, and the other the high-speed or fine dial. The speed refers to the ratio between the dial and the quantity whose motion it indicates. Thus a one-speed dial that indicates director train will make one revolution when the director turns one complete revolution. This dial can be read to about one degree, but the graduations are too close together to permit accurate reading to fractions of a degree. The high-speed train dial makes 36 revolutions for each revolution of the director, or one revolution for each 10 degrees of director motion. The degree marks are thus 36 times as far apart, and the dial can be read to one or two minutes or arc.

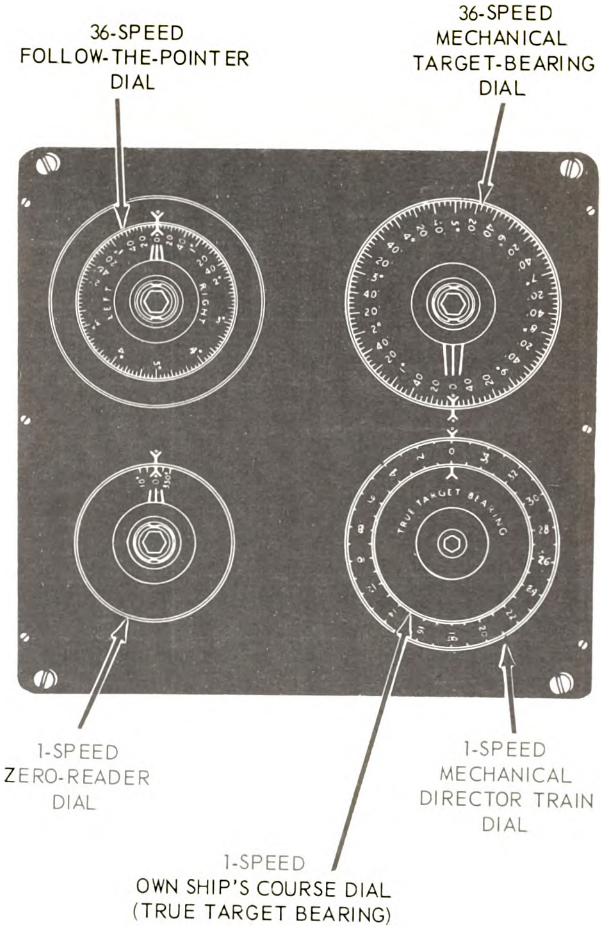
The high-speed dial repeats the same position and reading 36 times during one revolution of the director. Thus this dial must be used in combination with a low-speed dial. The two dials can be compared with the two hands of a clock. The low-speed dial corresponds to the hour hand which runs at two speed (two revolutions per day). This hand tells the hour but does not divide it accurately. The high-speed dial corresponds to the minute hand which runs at 24 speed (24 revolutions per day). This hand



12.272
Figure 6-21.—Radial-rollers and holding-down clips.

shows the exact minute of the hour, but does not show which hour.

The various pairs of dials in fire control equipment run at different combinations of speeds. For a part which cannot make a complete revolution, for example an elevation indicator, a two-speed or four-speed dial may be used as the low speed dial. Where great accuracy is required, the high-speed dial may operate at 72 speed or some higher multiple. Where accuracy is not critical, a single low-speed dial is used. Where a quantity may have either a positive or negative value—elevation for example—the color of the dial markings is often used to indicate polarity. White markings are used when the quantity is positive; red markings indicate a negative value.

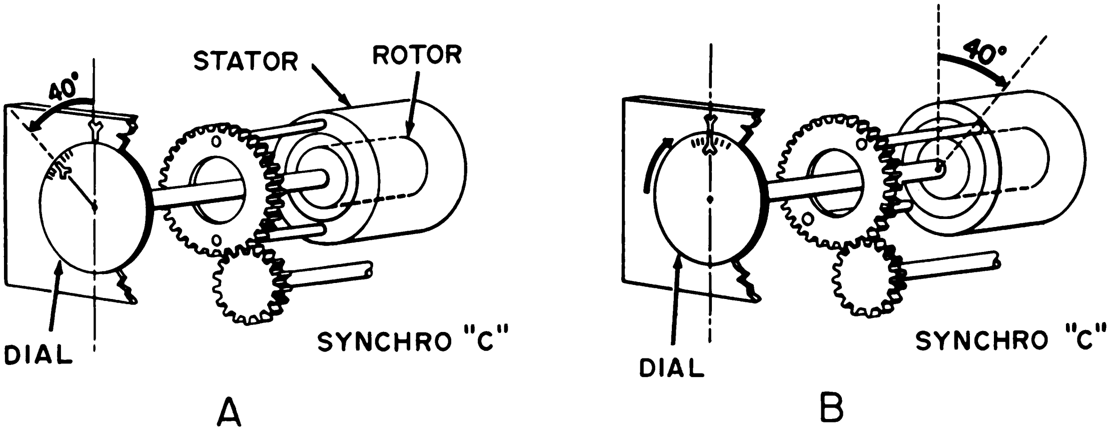

36-SPEED FOLLOW-THE-POINTER DIAL
36-SPEED MECHANICAL TARGET-BEARING DIAL
1-SPEED ZERO-READER DIAL
1-SPEED MECHANICAL DIRECTOR TRAIN DIAL
1-SPEED OWN SHIP'S COURSE DIAL (TRUE TARGET BEARING)
LEFT
RIGHT
TRUE TARGET BEARING

12.273
Figure 6-22.—Director train dial group.

Train Dial Group

A typical director train dial group is shown in figure 6-22. We will use this group to illustrate the operation of various types of dials. The lower left-hand dial in the group is a zero reader dial. The dial is mounted on the shaft of a one-speed synchro (fig. 6-23). The synchro is bearing mounted, and the whole synchro will turn with director train. The synchro is part of the target designation system. If the designation calls for the director to train right 40°, the synchro rotor will turn the dial 40° counterclockwise as shown in the figure. As the director is trained to the right, the synchro is turned clockwise. The dial turns with the synchro. Figure 6-23B shows the dial back at its original zero position, but the director has been trained to the right.

The zero-reader dial has sufficient accuracy to enable the director to be trained close to the target's bearing. Greater accuracy is attained by use of the 36-speed "Follow-The-Pointer" dial, which is the upper left-hand dial in the group shown in figure 6-22. The follow-the-pointer dial consists of two concentric dials. The inner dial is mounted on the rotor shaft of the 36-speed train designation synchro. The



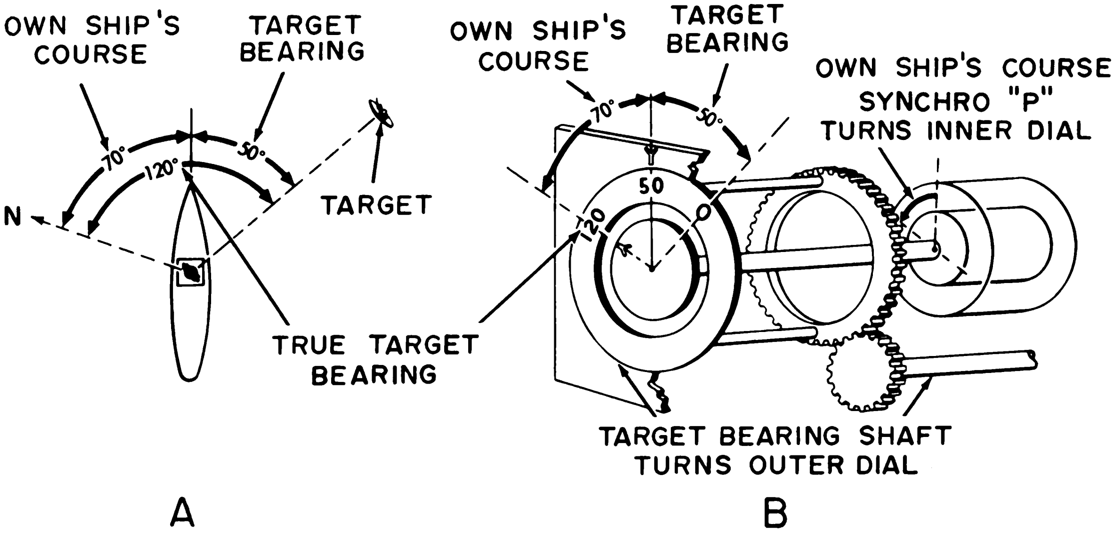
12.274

Figure 6-23.—Zero-reader dial.

inner dial turns with the synchro rotor. The outer dial is a ring dial driven by director train at 36 speed. Hence this dial indicates director motion. The movements of the two dials are independent of each other, but are related by the zero reference marks. When the two marks are aligned as shown in the figure, the director is at the designated bearing, provided that the zero-reader is at zero.

The true bearing of a target can be read from the pair of dials in the lower right-hand corner of the group (fig. 6-22). True bearing is the sum of target bearing and own ship's course as shown in figure 6-24A. The synchro in figure 6-24B receives own ship's course and turns the inner dial through this angle. In the example shown in the figure, the dial is turned 70° counterclockwise. The director train shaft turns the outer ring dial 50° clockwise as the director gets on target. By reading the graduations on the ring dial against the arrow of the inner dial, the sum of the two angles, 120° (which is true target bearing), can be read.

The upper right-hand dial in the group in figure 6-22 is a 36-speed dial, driven by the director train shaft. This dial shows director train at 36 speed. Director train at one speed is read from the ring dial below the 36-speed



12.275

Figure 6-24.—True bearing dial.

dial, by reading the dial against the fixed-index arrow (crow's feet) instead of the movable arrow.

The Veeder Counter

When making adjustments in rangekeepers and computers, it is necessary to count shaft revolutions. This is done with the Veeder counter.

No doubt you've seen counters used in automobiles to indicate milage. Well, the Veeder counter used in fire control works on the same principle. But instead of indicating milage, it counts the revolutions of a shaft value. The value that a shaft carries might be any value used in computing the fire control problem, such as yards of range, degrees of bearing, or target speed in knots.

Figure 6-25 shows a counter connected to a shaft by means of miter gears. In this case the counter serves a dual purpose: first, it is used for indicating proper adjustment; and second, it indicates revolutions of shaft value.

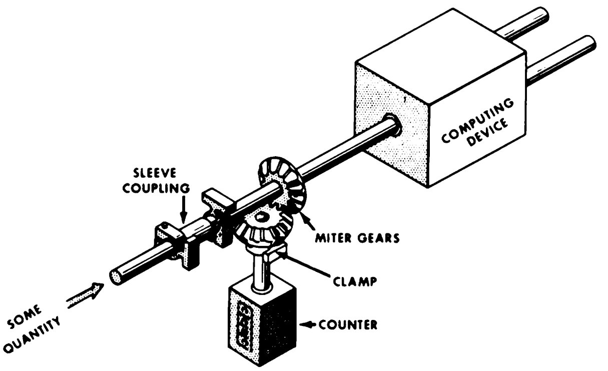
To perform an adjustment on the setup shown in figure 6-25 first set the computing device at its zero position. Then loosen the clamp at the counter and turn the counter until it, too, reads zero, and tighten the clamp. Now both the computing device and the counter are at their zero position.

Next, loosen the clamp at one end of the sleeve coupling and turn the input quantity until it and the counter are on zero at the same time. Finally, tighten the clamp of the sleeve coupling to complete the adjustment.

This type of counter is called an off-line counter, as it can be disconnected without affecting the adjustment.

It would be impractical to describe the many different dials found in fire control equipment. But the basic descriptions of dial indications can be applied to the reading of all dials. Briefly, the factors involved in reading dials are:

1. Reference position of the quantity indicated, and of the dial.
2. Units of measure of the quantity.
3. Dial speed, which governs the spacing of the dial graduations.
4. If two or more quantities are indicated by related dials, the relationship between the quantities must be known.



12.61

Figure 6-25.—Veeder counter.

ELECTRICAL COMPONENTS

In fire control circuitry, electrical signal and energizing voltage transmission is controlled by numerous switching devices. These devices can delay, interrupt, isolate, or integrate electrical circuits and prevent damage to equipment. This section is devoted to some of the more common switching and protective devices found in fire control equipment.

PROTECTIVE DEVICES

Fuses

The simplest and most common protective device is a fuse. Functionally, a fuse consists of a metal alloy strip or wire, and terminals for electrically connecting the fuse into the circuit. Most fuses are made of an alloy of tin and bismuth; but copper, aluminum, German silver, or iron alloys also have been used. All fuses are rated by the amount of current that is safety carried by the fuse element, and by voltage. Usually, the current rating is in amperes, but some fuses are rated in fractions of an ampere.

The fuse element is designed to melt when the current through it exceeds its rated value. Thus, when the circuit is overloaded, the fuse element melts and opens the circuit that it is protecting. However, all fuse openings are not the result of overloads. Aging of the fuse element, poor contact at the fuse holder, and the condition of the surrounding atmosphere will affect the time required for the element to melt. A fuse is always placed in series with a circuit so that it opens the circuit automatically, if excessive current is drawn.

DELAYED-ACTION OR TIME-DELAY FUSES.—Some equipment, such as electric motors, requires more current to start than for normal running. Thus, a fuse rating that will give running protection might blow during the period when high current is required. Delayed-action fuses have been developed to handle these situations.

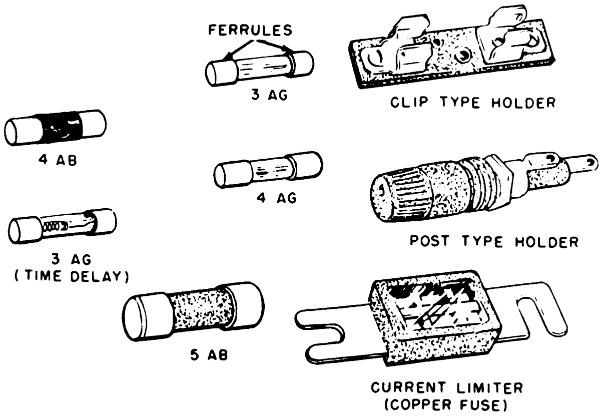
A heater element is connected in parallel with the fuse element in order to get the delayed action. During normal operation the heat developed in the fuse link is not great enough to melt the link. The melting, or opening, of the fuse link depends on the transfer of heat to the link from the heater. Therefore, more time is needed to melt the link than would be required if the link were directly heated.

Because the heater and fuse element are in parallel, the opening of the fuse element will cause the total circuit current to flow through the heater. The high current will cause the heater to burn out and completely open the circuit.

Another type of delayed-action fuse has the fuse element and heater connected in series. Current above that of the rated value for a short time will not open the fuse or heater. However, prolonged overloads cause the heater section to become hot enough to melt the junction between the elements and open the circuit.

Delayed-action fuses are sometimes called ''slow-blow'' fuses, and two trade names, Fusestat and Fusetron, are in common use.

CARTRIDGE FUSES.—Cartridge fuses are made in various physical sizes. The more common types of these fuses and their holders are shown in figure 6-26. The current capacity of each fuse is marked on the side of one of the ferrules (end caps). The size is indicated by the AG or AB number. The AG indicates a glass body and the AB a bakelite body. Listed below are the dimensions of the standard AG and AB numbers.



12.64
Figure 6-26.—Cartridge fuses and fuse holders.

1 AG or 1 AB is 5/8 in. long and 1/4 in. in diameter.

3 AG or 3 AB is 1 1/4 in. long and 1/4 in. in diameter.

4 AG or 4 AB is 1 1/4 in. long and 9/32 in. in diameter.

5 AG or 5 AB is 1 1/2 in. long and 13/32 in. in diameter.

These fuses are rated at 80 percent of the current that they will carry indefinitely. The INSTANTANEOUS fuse must be able to carry a current 10 percent greater and must open the circuit at a current 25 percent greater than the fuse rating.

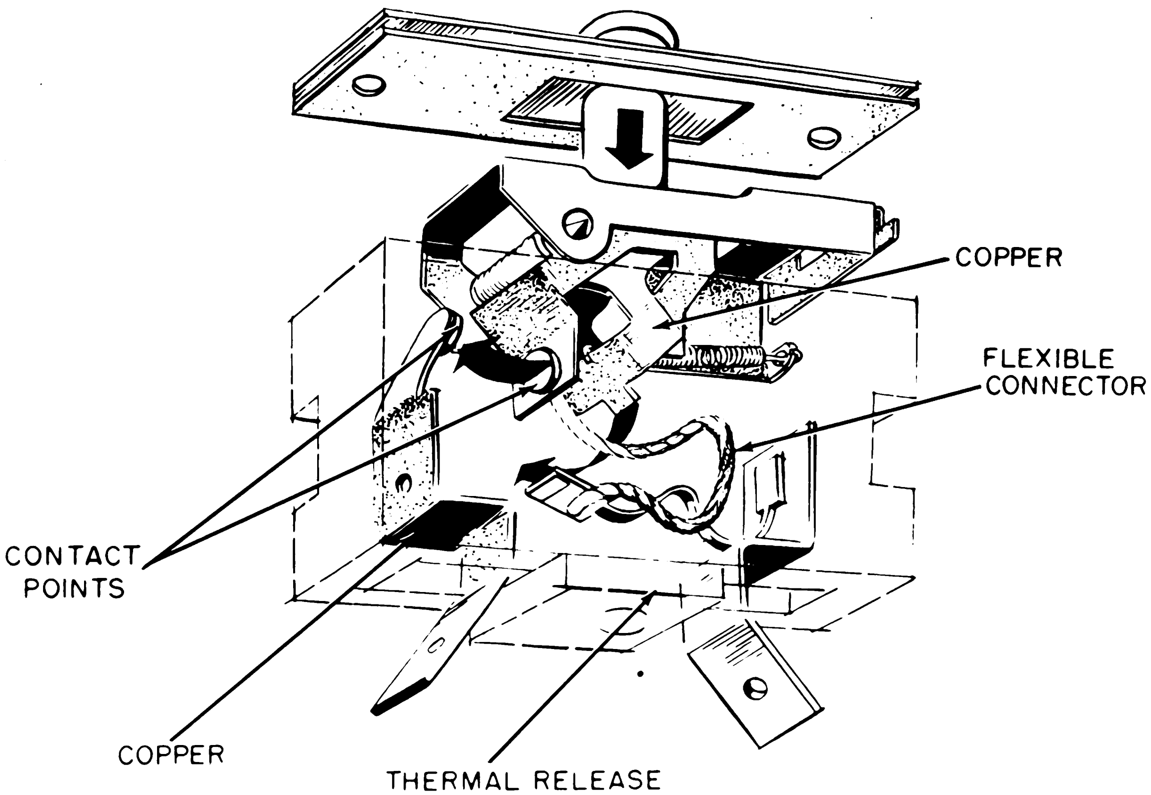
Circuit Breakers

In most fire control equipment a comparatively small device plays the role of guardian over the electrical system. This key to safety is the CIRCUIT BREAKER. It is designed to open the circuit under short-circuited or overloaded conditions without injury to itself. Thus it performs the same function as the fuse, but has the advantage that it is capable of being reset and used again. Like the fuse, the circuit breaker is rated in amperes and voltage.

While there are three basic types of circuit breakers (thermal, magnetic, and thermomagnetic), our main considerations will be directed toward the thermal type because it is at present more universally used. Circuit breakers will be divided into three categories—the pushbutton reset, the toggle type, and the automatic reset type (sometimes called a circuit protector).

The PUSHBUTTON reset type consists of a bimetallic, thermally (heat) actuated, spring-loaded device which closes the two electrical contacts when set. This is shown in figure 6-27. An excessive current through the device causes an uneven expansion of the bimetallic mechanism (thermal release) which releases a trigger escapement. This release permits the spring loading to rapidly separate the movable and stationary contact members.

A visual indication of the automatic opening is provided by causing the pushbutton to move to an easily noticed ''tripped'' position. In this position the button is fully extended, and the



12.65

Figure 6-27.—Thermal circuit breaker.

white ring plus the inner red section of the button are showing. The latest type of pushbutton breakers have a pullout feature which permits manual opening of the circuit, but this type should NOT ordinarily be used as a switch.

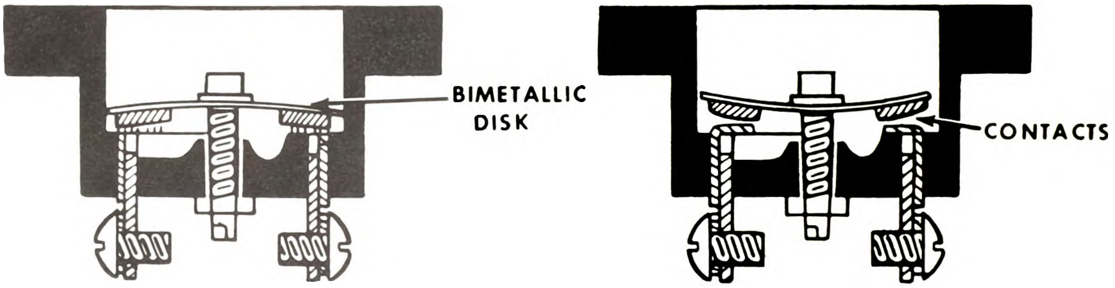
In place of the pushbutton actuator, a toggle lever is used on another type of circuit breaker. It operates like the previously discussed breaker, except that the tripped position is indicated by the toggle lever being in the OFF position. This type of circuit breaker can be used as a switch.

Manual resetting of the circuit breaker may be accomplished by means of the actuator (either pushbutton or toggle lever) whenever the bimetallic thermal element cools sufficiently for the trigger to engage its latching mechanism. In connection with resetting there are two other classifications for circuit breakers: namely, trip-free and non-trip-free. The non-trip-free circuit breakers can be maintained closed by the operator's action while a tripping condition exists. This should be done only in an emergency.

In the trip-free class the contacts cannot be maintained closed by manually holding the actuator in the reset position as long as an overload condition persists.

Another type of thermal circuit breaker is shown in figure 6-28. This breaker consists of a conductive bimetallic snap-acting disk which bridges two electrical contacts. When the disk is heated by an excess current it snaps into reverse position, opening the contacts and the circuit. In circuit breakers having low ratings, a resistance wire is inserted in the circuit. The resistance wire provides the heat necessary to snap the disk. The circuit is reset by pressing the button which restores the disk to its original position. Once this type of circuit breaker is closed it cannot be reopened manually. They are also nonindicating; that is, the position of the breaker (open or closed) cannot be determined by visual inspection.

The automatic-reset type circuit breaker is similar to the bimetallic disk type just described, except that it has no reset pushbutton; it resets itself automatically. After a



5.82A

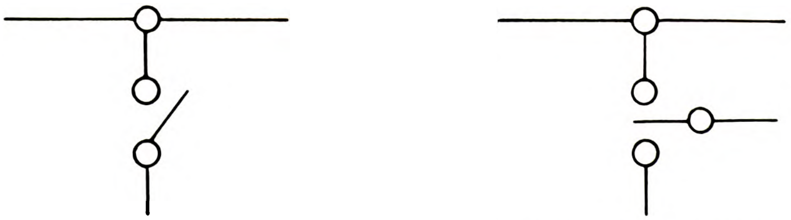
Figure 6-28.—Thermal circuit breaker.

short time, when the disk has cooled sufficiently, it will bend back and close the circuit, resetting itself. If a constant overload exists, the breaker will intermittently break the circuit.

Another type of circuit breaker is the switch toggle variety based on magnetic instead of thermal operation. This type can be made to open almost instantly when more than the rated current flows in the circuit. To accomplish this, an electromagnet is placed in series with the contacts and the contacts are mounted on an armature. When an excess current flows through the device, the armature will be pulled toward the electromagnet, opening the contacts and thereby the circuit. The armature is then latched in the off or tripped position. To reset the circuit breaker, the armature is unlatched and returned to the normal position.

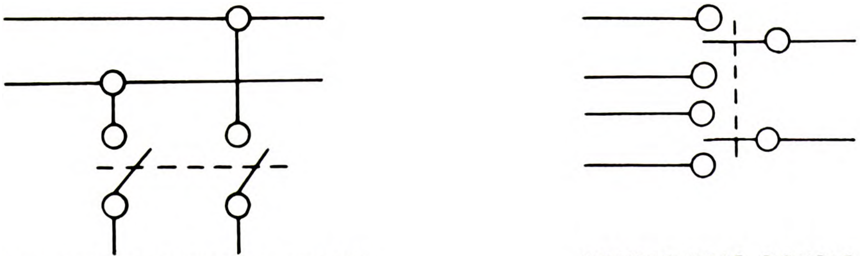
SWITCHES

A switch may be described as a device used in an electrical circuit for making, breaking, or changing connections. Switches are rated in amperes and volts; the rating refers to the maximum voltage and current of the circuit in which the switch is used. Because it is placed in series, all the circuit current will pass through the switch. Because it opens the circuit, the applied voltage will appear across



SINGLE - POLE, SINGLE - THROW
(SP ST)

SINGLE-POLE, DOUBLE-THROW
(SP DT)



DOUBLE-POLE, SINGLE-THROW
(DP ST)

DOUBLE-POLE, DOUBLE-THROW
(DP DT)

12.66

Figure 6-29.—Commonly used switches; schematic diagram.

the switch in the open position. Switch contacts are opened and closed quickly to minimize arcing; therefore, switches normally have a snap action.

Many types and classifications of switches have been developed. A common designation is by the number of poles, throws, and positions they have. The number of poles indicates the number of terminals at which current can enter the switch. The throw of a switch signifies the number of circuits each blade or contactor can complete through the switch. The number of positions indicates the number of places at which the operation device (toggle, plunger, etc.) will come to rest. Figure 6-29 presents the schematic diagrams of some often used switches.

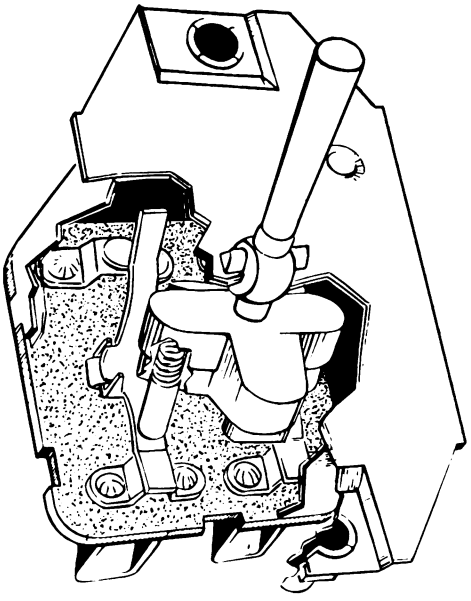
An example of a switch position is a toggle switch which comes to rest at either of two positions, opening the circuit in one position and completing it in another. This is called a two-position switch. A toggle switch which is spring loaded to the OFF position and must be held in the ON position to complete the circuit is called a single-position switch. If the toggle switch will come to rest at any of three positions, it is called a three-position switch.

Another means of classifying switches is the method of actuation; that is, toggle, pushbutton, precision, and rotary types. Further classification can be accomplished by a description of switch action such as on-off, momentary on-off, on-momentary off, and so forth. Momentary contact switches hold a circuit closed or open only as long as the operator deflects the actuating control.

TOGGLE SWITCHES are one of the most common types of manual switches. Toggle switches have their moving parts enclosed. A double-pole, double-throw, on-off-on toggle switch is shown in figure 6-30. These switches have many uses and are used extensively for applying power to various circuits, such as low voltage power supplies.

PUSHBUTTON SWITCHES have one or more stationary contacts and one or more movable contacts. The movable contacts are attached to the pushbutton by an insulator. This switch is usually spring loaded and is of the momentary contact type. These switches have many uses, such as indicator light checks and motor start and stop circuits.

The contact arrangement of push switches is shown in figure 6-31A, and an example of a typical contact arrangement is shown in part B.



12.67

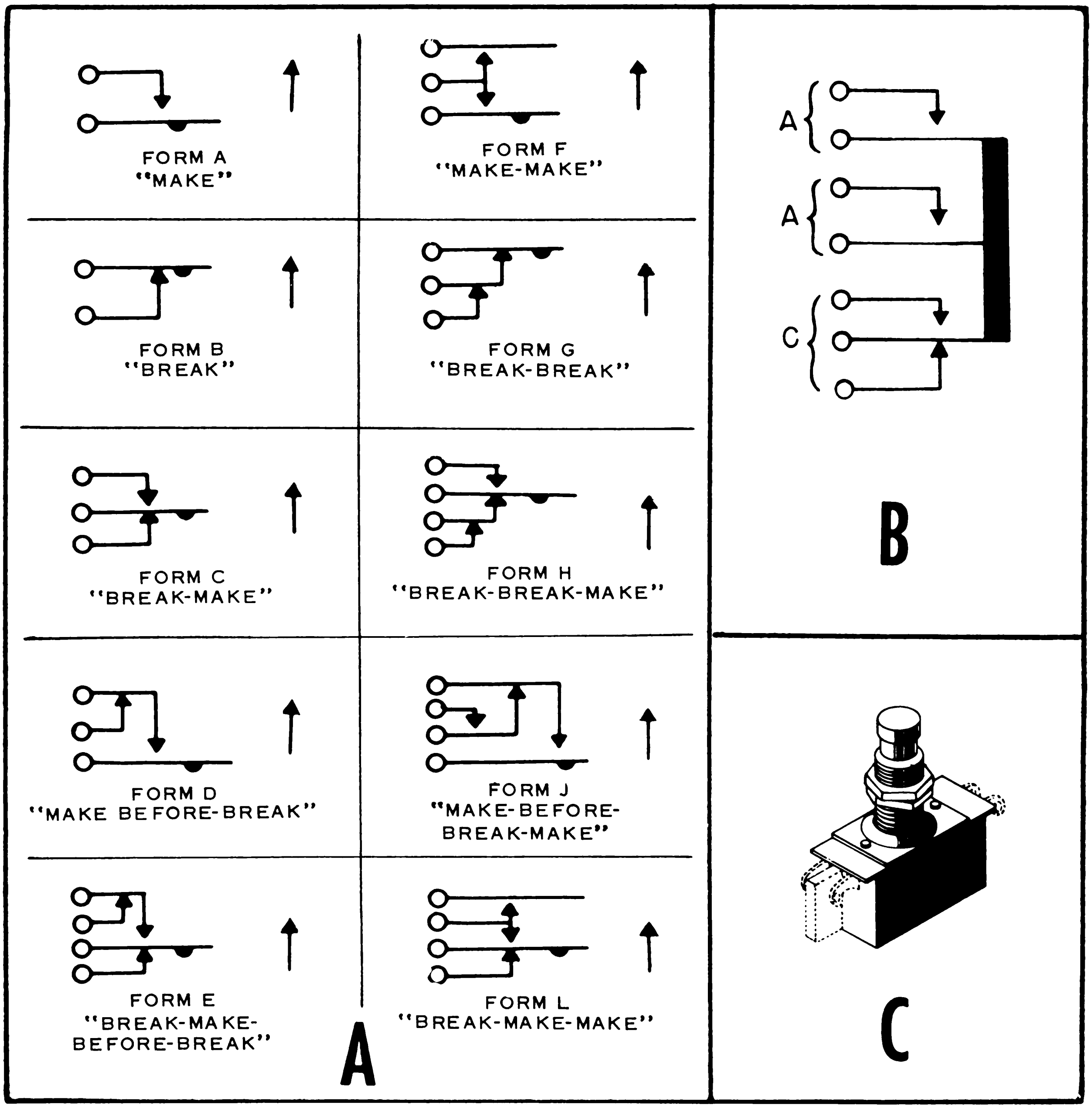
Figure 6-30.—Toggle switch.

The type and quantity of each basic form used to make up the contact assembly are determined from part A. Part B shows how the illustrations in part A may be used in a practical switch assembly. Thus, in part B the switch contains a total of three separate basic forms: two forms A, and one form C. The contact arrangement for this switch is therefore 2A1C. Obviously, there are many possible contact arrangements. For example, 1A, 1A1A, 1A1B; 2A, 2A1B, 1B, etc., are common.

A push switch employing a 2A contact arrangement is shown in figure 6-31C. It is rated at 250 v and 3 amperes.

A ROTARY SELECTOR SWITCH may perform the functions of a number of switches. As the knob of a rotary selector switch is rotated, it opens one circuit and closes another. This can be seen from an examination of figure 6-32. Some rotary switches have several layers of wafers. By adding wafers, the switch can be made to operate as a large number of switches. Voltmeter range selector switches are examples of this type.

The KNIFE SWITCH (fig. 6-33) is another common type of switch. It is used to open and close power circuits to motors, and other equipment using large amounts of current. A single-pole, single-throw knife switch consists of a single copper blade hinged at one end and designed to fit tightly between two copper jaws, or

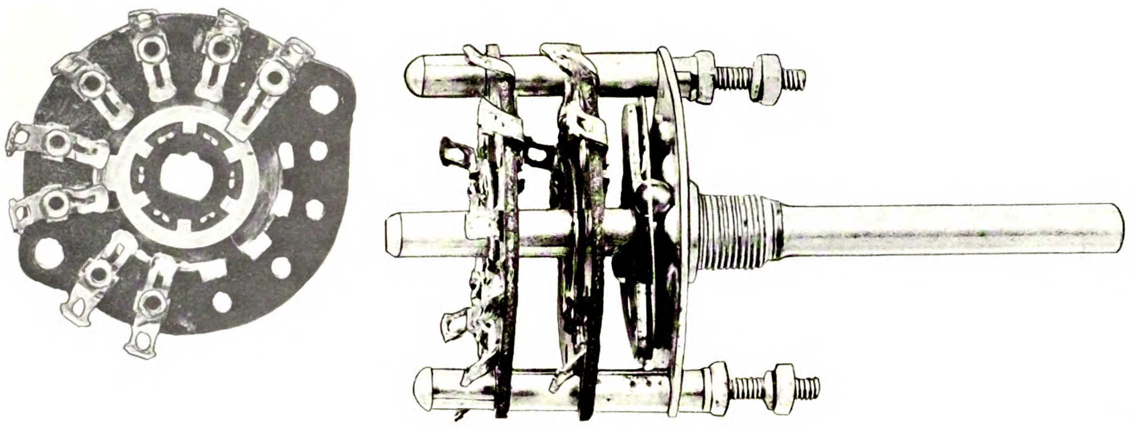


1.99

Figure 6-31.—Push switches.

clips, at the other end. An insulated handle is fastened to the copper blade to open and close the switch. Terminals are provided for connecting the leads. Knife switches are rated according to their current-carrying capacity at a specified voltage.

The current rating depends on the cross-sectional area of the blade and the contact area of the clips and hinges. The voltage rating depends on the length of the blade and the space between blades when there are two or more. If the blade is too short, the arc which occurs when



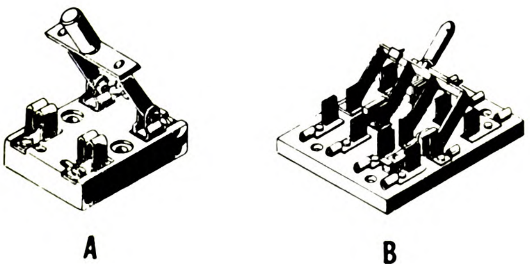
12.68

Figure 6-32.—Rotary switch.

the current is interrupted may travel down the blade and be maintained across the open switch.

Knife switches are made in a variety of types. A two-pole, single-throw knife switch has two blades with one set of clips for each blade, and an insulated handle that operates both blades simultaneously. Double-throw switches have two sets of clips—one set at each end—so the blades can be thrown into either set of clips to shift from one circuit to another.

The SNAP SWITCH is a device that opens or closes a circuit with a quick motion. A rotary snap switch consists of one or more sections each of which has a rotor and a stationary member (fig. 6-34). A shaft with a handle at one end extends through the center of the rotors. The rotors are snapped in and out of the stationary contacts on the pancake sections. When the handle is turned, it first winds a coil spring on the shaft. As the handle is turned farther, the coil spring snaps the rotor contacts in or out of the stationary contacts.

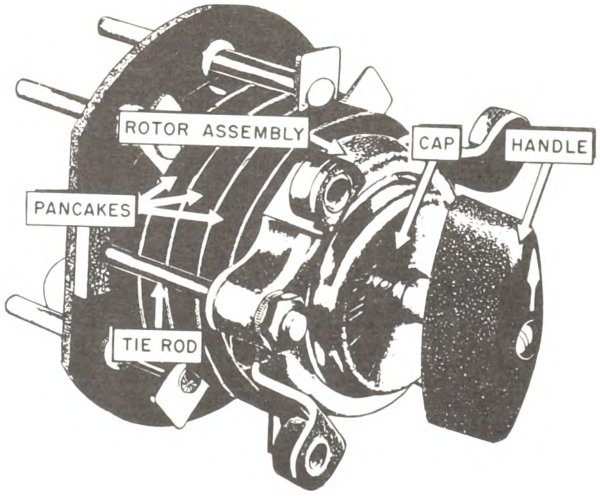


1.102

Figure 6-33.—Knife switches.

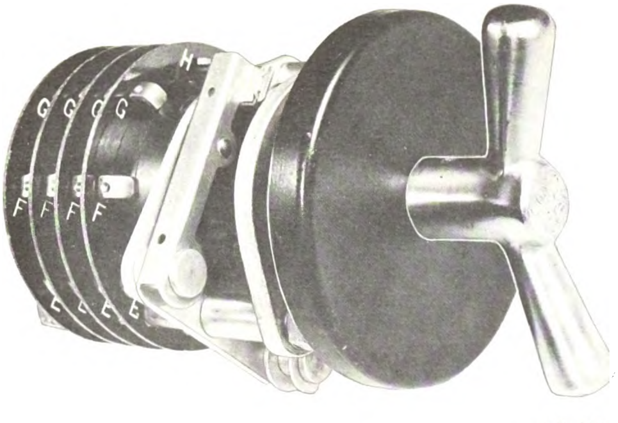
Snap switches are available in a wide variety of current ratings, poles, movements, and circuit arrangements. Most of these switches are suitable for operation on a-c at 600 volts and d-c at 250 volts. Snap switches are used extensively in the distribution sections of switchboards, to connect the power supplies to the various buses.

The type—J MULTIPOLE ROTARY switch consists of an equal number of rotors and pancake sections, as illustrated in (figure 6-35). The number of sections required in the switch is determined by the individual application. A shaft with an operating handle extends through the center of the rotors. The movable contacts are mounted on the rotors, and the stationary



12.69

Figure 6-34.—Snap switch.



12.70

Figure 6-35.—Type-J switch.

contacts are mounted on the pancake sections. Each section consists of eight contacts, designated A to H, and a rotor having two insulated movable contacts spaced 180° apart. Each movable contact is arranged to bridge two adjacent stationary contacts. The switch has eight positions. A detent mechanism is provided for proper alinement of the contacts in each position of the operating handle. In one position, the rotor contacts bridge segments A-B and E-F. In the next position, the rotor contacts bridge segments B-C and F-G. Diagonally opposite pairs of contacts are subsequently bridged for the remaining positions. The various circuit leads are connected to the proper pancake terminals and the transfer of circuits is effected by operating the handle.

The JR SWITCH shown in figure 6-36A, is installed on FC, recent IC, and ACO switchboards. This switch is smaller in size and more readily disassembled than the J switch. These features result in a saving in switchboard space and facilitate repairs. The JR switch is of the 1JR, 2JR, 3JR, or 4JR type.

The 1JR switch has only one movable contact per section. This movable contact bridges two adjacent stationary contacts.

The 2JR switch is the same electrically as the J switch, and is the type used for general applications.

The 3JR switch utilizes one of the stationary contacts as a common terminal. This stationary contact is connected in turn to each of the other stationary contacts of the section by a single wiper contact. The 3JR type is used for selecting one of several (up to seven) inputs.

The 4JR switch has two movable contacts per section. Each movable contact bridges three adjacent stationary contacts (fig. 6-36B). This switch is used to select either or both of two synchro indicators. The positions of the switch are:

90° right—both indicators energized
45° right—indicator 1 energized
0°—off
45° left—indicator 2 energized

When the 4JR switch is in the OFF position, both indicators are connected together but are disconnected from the power supply.

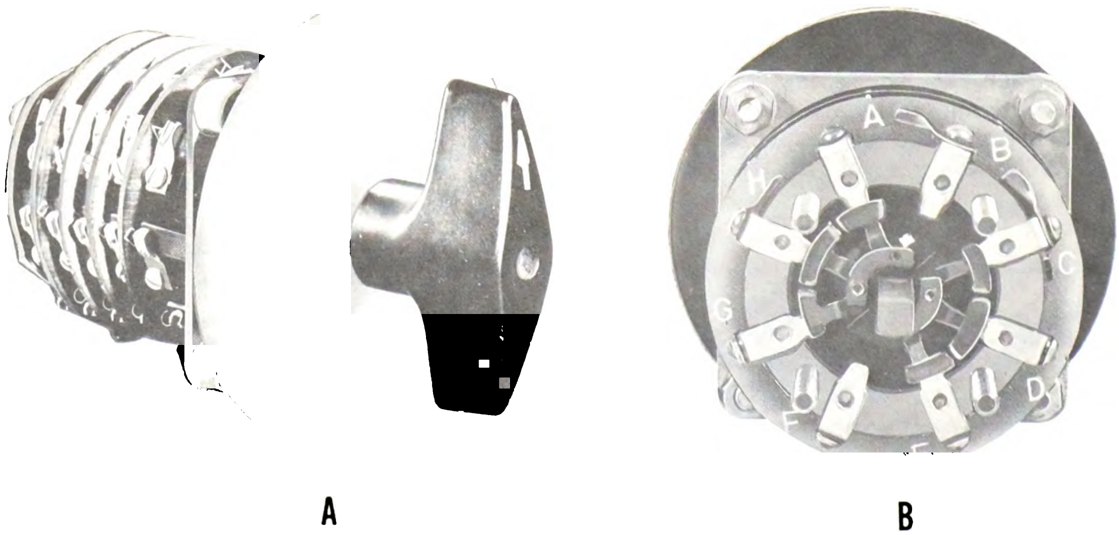


Figure 6-36.—Type-4JR switch. 12.71

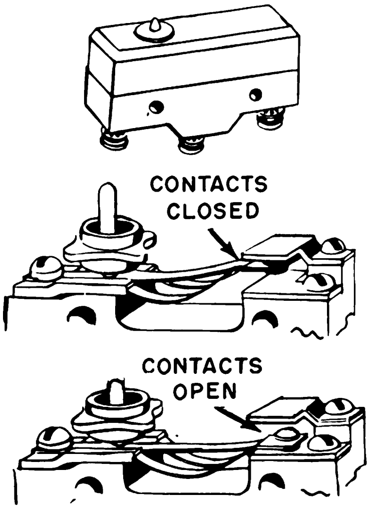
The designations of JR switches are determined by the type of section, followed by the number of sections in the switch. For example, a 2JR10 switch denotes a JR switch having 10 type-2JR sections. Other common multiple rotary switches are the JA, JP, and JRP types.

SENSITIVE SWITCHES are small, short-travel, snap-action switches. They are manufactured as (1) normally open, (2) normally closed, and (3) double throw. The latter has no OFF position. The term MICROSWITCH, although frequently used in referring to all switches of this type, is a trade name for the switches made by the Micro Switch Division of Minneapolis Honeywell Regulator Co.

Sensitive switches are usually of the push-button variety and are often used as limit switches. These switches usually depend upon one or more springs for their snap action. For example, the heart of the microswitch is a beryllium copper spring. The simplicity of the one-piece spring contributes to the long life and dependability of this switch. The micro-switch is shown in figure 6-37.

RELAYS

Relays are electrically operated switches that are classified according to their use as control relays or power relays. The POWER RELAYS are the workhorses of electrical systems. As such, they control the heavy power circuits.



12.72
Figure 6-37.—Microswitch (sensitive switch).

The function of a CONTROL RELAY is to take a relatively small amount of electrical power and use it either to signal or to control a large amount of power. For example, control relays are used to start and stop electric motors. The heavy power relays that actually apply the power to the motor are the MAIN LINE CONTACTORS. The relays that control the main line contactors are control relays.

Also control relays may act in somewhat the same capacity as a vacuum tube amplifier in an electric circuit. While the vacuum tube is ordinarily used to amplify voltage, the relay usually amplifies current or power. The use of relays saves space and weight in the ship by permitting the use of small switches at remote control stations. These switches permit the operator to control large amounts of current at other locations in the ship, and the heavy power cables need to be run only to the point of use. Only lightweight control wires are connected to the control switches. Safety is also an important factor in using relays, since high power circuits can be switched remotely without danger to the operator.

Control relays, as their name implies, are frequently used in the control of other relays, although the small control relays find many other uses. With these, electron tube plate currents can control the larger currents necessary to operate electrical devices. They find extensive use in weapon direction equipment circuits, where a small electric signal sets off a chain reaction of successively acting relays performing various functions, such as target designation and weapon assignment. Control relays can also be used to prevent certain functions, such as gun firing, or missile launching, from occurring at the improper time. Various electrical operations in the equipment which must not occur simultaneously can be "interlocked" by control relays. Another important function of control relays in fire control equipment is for "sensing." Control relays are used for sensing undervoltage and overvoltage, reversal of current, and excessive currents.

Another possible classification of relays is open, semisealed, and sealed. Semisealed relays have protective covers and are gasketed against entrance of salt, dust, and foreign material into the contact or mechanism area.

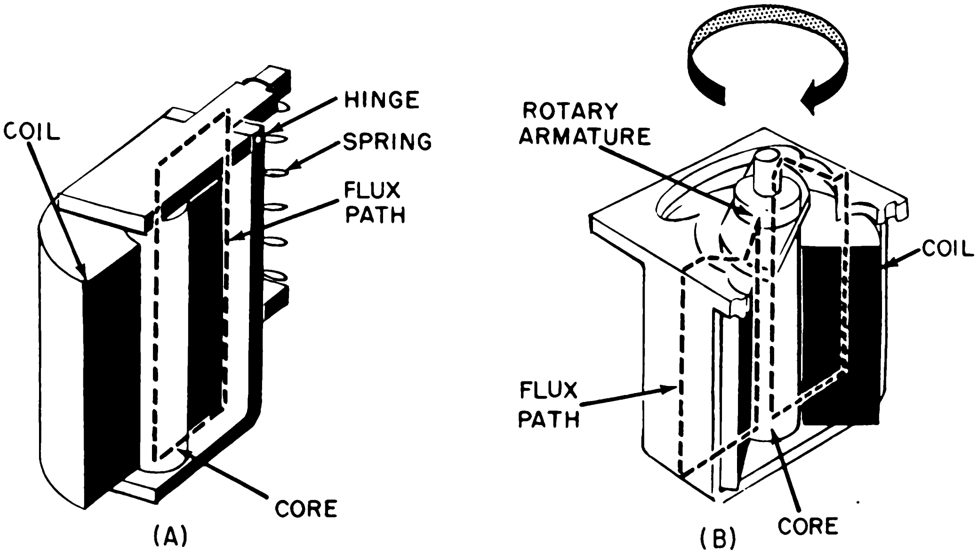
For other applications in today's far-ranging ships, however, it is necessary to go beyond the protection offered by the open type and the semisealed relays. When such relays are used, quick changes in climatic conditions (humidity and temperature) can cause condensation of water vapor within the unit. Subsequent low temperature will then freeze the moisture on the contactor, with a resultant inability to carry electric current.

Hermetically sealed relays were developed to answer the demands of most modern equipment. A true hermetic seal is generally considered one that is metal-to-metal or glass-to-metal. Plastic or plastic-rubber type gasket seals are not generally considered true hermetic seals. However, both semisealed and hermetically sealed relays are used. There are applications where a gasket type sealed relay may be adequate, but the true hermetically sealed type is generally considered to be more permanent. The hermetically sealed relay also has the advantage of being protected from improper adjustments.

In general, the basic components of a relay are the coil or solenoid, the iron core, the fixed and movable contacts, and the mounting (and if sealed, the can). A manual switch, limit switch, or other small control device starts and stops the flow of current to the coil. The flow of electric current through the coil creates a strong magnetic field around and within the coil. This magnetic field moves a clapper or plunger which completes the magnetic circuit. Figure 6-38A shows a basic single coil clapper type relay. The dashed lines indicate the magnetic lines of flux. For a more complete analysis of the theory of operation see Basic Electricity, NavPers 10086-A.

The second basic type of relay is the rotary (fig. 6-38B). Although this type of construction is not as common as the clapper type, the rotary type has greater vibration and shock resistance than the others. The disadvantage is that they are somewhat sluggish and require higher operating power for many purposes. The rotary relay operates on the principle of an electric motor, but through only a small arc. The problem of hanging contacts on such a mechanism is a difficult one, and therefore the use of these devices is limited to applications where high shock warrants the larger size and weight. When used with standard wafer switch assemblies, this type of relay provides a means for assembling a switching device of any degree of complexity.

You will encounter relays operating from an a-c supply; they depend on the same fundamental principles as the d-c relay; that is, magnetic fields. When a-c is applied to an electromagnet, the current will pass through zero twice in each cycle. Since the pull on the armature is proportional to the current through the electromagnet, the armature tends to open



12.73

Figure 6-38.—Basic types of relays.

every time the current nears zero, causing chatter. To remedy this, shading coils (sometimes called shaded poles) are used.

A shading coil consists of a copper band or stamping which is short-circuited and embedded around part of the electromagnet pole face. By being placed around part of the pole face, it acts as a shorted transformer secondary. The current in the main coil lags the applied voltage by approximately 90° and the flux is in phase with the current. The voltage of the shading coil is induced voltage and lags the current in the main coil by 90 degrees. Since the shading coil acts like a shorted secondary (resistive), the current in the shading coil is in phase with the induced voltage. Therefore, the magnetic field of the shading coil lags the magnetic field of the main coil by 90 degrees. This means that flux will exist in the electromagnet even when the main coil current becomes zero. Thus, chattering is prevented.

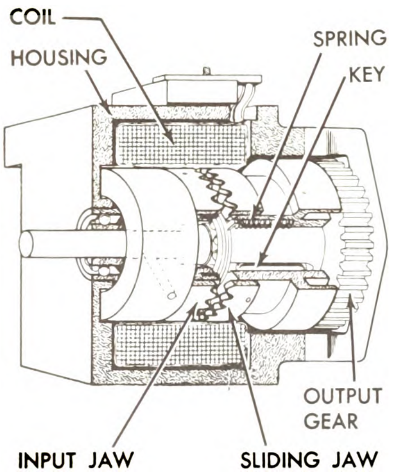
The arrangements of relay contacts are found in many different forms. Usually the number and sequence of switching operations to be performed dictates the contact arrangement.

It is often desirable to introduce time delays by use of relays. One method is to use a thermal relay for a time delay. In operation, this relay is similar to the thermal circuit breaker except that it closes the circuit rather than opens it when heated. Due to the simple mechanism, it can be made very small and hermetically sealed, making it ideal for use in fire control equipment. Because the thermal relay is activated by heat, it can be used on either alternating or direct current.

SOLENOID CLUTCH OR LOCK

A solenoid clutch or lock controls a mechanical line in the same way a control relay controls an electrical circuit. Figure 6-39 shows a solenoid clutch. The input shaft rotates one jaw. The other jaw is mounted on the hub of the output gear. This is the sliding jaw, and it is free to move on keys which are set between the jaw and the hub of the gear. The keys prevent the jaw from turning on the hub. Three springs hold the sliding jaw out of engagement with the input jaw when the coil is not energized.

When the coil is not energized the input shaft and jaw may turn, but they have no effect on the output gear—the two jaws are not connected. Hence the mechanical line is broken by the absence of an electrical signal.



12.276

Figure 6-39.—Solenoid clutch.

When the coil is energized, it pulls the sliding jaw into mesh with the input jaw. In this position the two jaws turn together, and the output shaft is driven by the input shaft.

Operation of a solenoid lock is similar to that of a clutch, except that in the lock one jaw is pinned to the frame and the input operates the sliding jaw. When the coil is energized, the sliding jaw is pulled into mesh with the pinned jaw. The pinned jaw cannot rotate, and the input line is locked in this position. When the coil is not energized the springs pull the jaws out of mesh. In this position the input can turn freely.

CABLING

Types of Cables

The various electronic systems aboard ship depend on power supplied by the ship's service generators. This power is distributed to the electronics spaces by a system of cables. Power cables are normally installed by shipyard forces, but the FT should know in detail the location and characteristics of the cabling that supplies the equipment with which he works.

He should become familiar with the current-carrying capacity of cables; their insulation strength; and their ability to withstand heat, cold, dryness, bending, crushing, vibration, twisting, and shock. Several types of cables are used in the applications under discussion, with design characteristics suited to their location and purpose.

Type SGA (Shipboard, General use, Armored) cables are designed to have a minimum diameter and weight consistent with service requirements in fixed wireways on combatant naval vessels. This type supersedes the older, widely used type HFA (Heat and Flame resistant, Armored) cable.

Type SSGA cable (fig. 6-40) consists of stranded copper conductors (in this case, only one conductor—indicated by the "S" before SGA) insulated with silicone rubber and glass fibers around which is placed an impervious sheath. The sheath is covered with braided metal armor, and then a coat of paint is applied.

The SGA cables are designated as follows: (1) SSGA, single conductor; (2) DSGA, twin (double) conductor; (3) TSGA, three conductor; and (4) FSGA, four conductor.

The HFA cables (also composed of stranded copper conductors) are designated as follows: (1) SHFA, single conductor; (2) DHFA, twin (double) conductor; (3) THFA, three conductor; (4) FHFA, four conductor; and (5) MHFA, multiconductor.

Twisted-pair telephone cables are designated as TTHFWA.

Many applications aboard ship require cables that can be bent and twisted again and again without damaging the conductor insulation or the protective covering. For such applications, flexible cables are used.

Flexible cables have synthetic rubber or synthetic resin insulation and a flexible sheath that is resistant to water, oil, heat, and flame. However, these cables are not as heat and flame resistant as armored HFA and SGA cables. Flexible cables for general use are designated by the letters HOF—for example, DHOF, THOF, and FHOF. Flexible cables for limited use are designated by the letters COP—for example, DCOP, TCOP, and FCOP.

Other types of cables used in electronics work are:

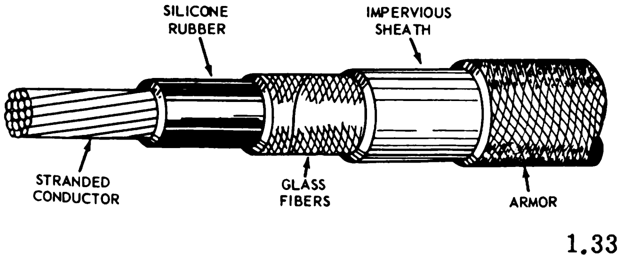
1. DRHLA—Double conductor, radio, high-tension, lead armored.
2. FHFTA—Four conductor, heat and flame resistant thin-walled armor.
3. MCSP—Multiple conductor, shielded pressure resistant (submarine applications).
4. TTRSA—Twisted-pair telephone, radio shielded, armored (characteristic impedance approximately 76 ohms).

DESIGNATION OF CONDUCTOR SIZE.—Generally, when the size of the individual conductors contained in the cable is indicated in the cable designation, the numeral (or numerals) following the letter designation indicate the approximate cross-sectional area of the individual conductors in thousands of circular mils to the nearest thousand. For example, TSGA-60 is a 3-conductor armored cable for general shipboard use, with each conductor having a cross-sectional area of 60,090 circular mils. However, when the numerals immediately following the letter designation indicate the number of conductors comprising the cable, the size of the individual conductors may be indicated by additional numerals enclosed in parenthesis. For example, MDGA-19(6) is a 19-conductor electrical power cable for shipboard nonflexing service, with each conductor having a cross-sectional area of 6,512 circular mils.

MULTIPLE-CONDUCTOR CABLE DESIGNATIONS.—Multiple-conductor cable types and class designations are followed by a number that indicates the number of conductors. For example, MSCA-30 is a heat and flame resistant armored cable with 30 conductors.

For telephone cable, the number indicates twisted pairs. For example, TTHFWA-25 means that the cable contains 25 twisted pairs; TTRSA-4 means that the cable contains 4 pairs individually shielded.

SELECTION AND INSTALLATION OF CABLES.—You should have some knowledge of the power cables feeding fire control equipment. There are at least five items that must be considered when power cables are installed. They are (1) the maximum connected load in amperes, (2) the possible added load due to future installations, (3) the demand factor (that is, the average demand in amperes over a 15-minute interval divided by the total connected load in amperes), (4) the cable service rating (the physical characteristics required for a given type of service), and (5) the maximum



1.33

Figure 6-40.—SSGA cable.

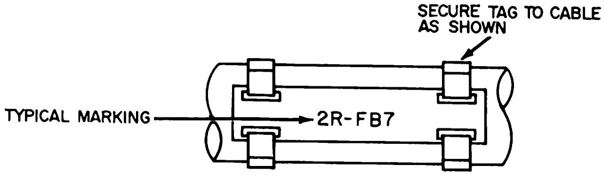
allowable voltage drop in the part of the circuit under consideration.

The current-carrying capacity and voltage-drop limitations determine the cable size for a particular application. The current capacity is dependent upon the type and size of the conductor, the permissible temperature rise, and the physical characteristics of the space in which the cable is installed. The allowable voltage drop depends on the type of load connected to the circuit.

All connections to cables are made in standard appliances and fittings; splice connections are not made. However, cable splices are permitted as an emergency repair (by ship's force), and on a limited basis (by repair activities) where it has been determined that time and replacement cost is excessive, and existing cable is in good condition. Cables entering watertight equipment are brought into the equipment through stuffing tubes (stuffing tubes and kickpipes are discussed later). Where cables pass through decks and watertight bulkheads, stuffing tubes are used. Cables passing through decks are protected from mechanical injury by kickpipes or riser boxes.

Cable Tags

All ship's cables are identified by metal tags. For example, electronic cable designation 2R-FB7 (fig. 6-41) will illustrate the method of marking the cables between units of equipment. The 2R-FB indicates the second guided missile fire control radar on the ship, R indicates electronics, FB indicates a guided missile radar circuit, and 7 indicates cable number 7 of the guided missile radar. For additional information see General Specification for Ships of the United States Navy, sections S28-2 and S71-1.

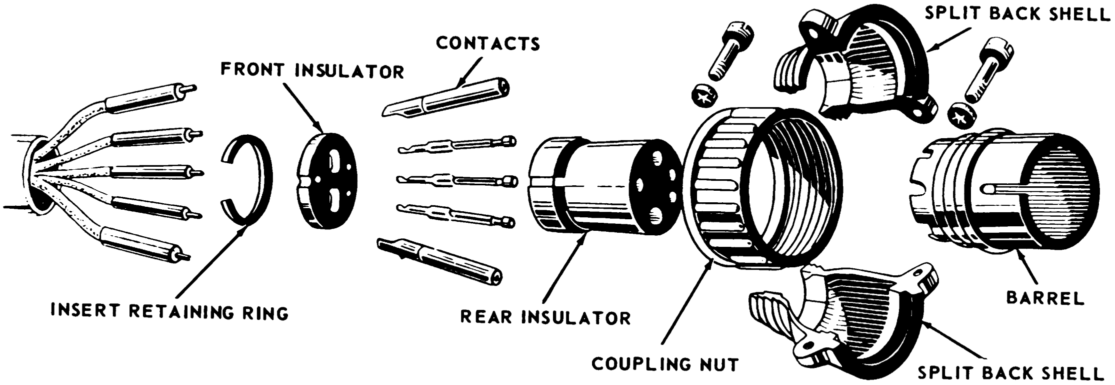


12.74
Figure 6-41.—Typical cable tag.

CONNECTORS

Connectors are devices attached to the ends of cables and sets of wires to make them easier to install and remove. Connectors consist of two parts: the fixed parts, called the receptacle, and the movable parts, called the plug. Plug assemblies may be of the straight type or the 90-degree type, while receptacle assemblies may be the wall-mounting, box-mounting, and integral-mounting types. Army-Navy specification numbers and letter identify the type, style, and arrangement of a connector. AN connectors are designed to provide detachable connections between electrical circuits in fire control equipment. They are constructed to withstand the extreme operating conditions imposed by this service. Connectors used in these electrical circuits must make and hold electrical circuits securely and without undue voltage drop despite extreme vibration, rapid shifts in temperature, and vast altitude differences.

Basically, the plug and receptacle assemblies each consist of an aluminum shell containing



12.75
Figure 6-42.—AN connector plug; exploded view.

an insulating insert which holds the current-carrying contacts. This basic design permits a wide variation in shell type, design and size, contact layout, and insert style. An exploded view of a connector plug is shown in figure 6-42.

There are eight shell types of AN connectors in use. Their number and nomenclature, which are mostly self-descriptive, are given in table 5-1, and are shown in figure 6-43. Integral is used in the sense that the plug or receptacle is an integral part of the equipment housing.

AN connector shells are also designed under five different classes for particular applications. The different classes are signified by a letter after the AN number. The letters and their meanings are: (A) solid shell, (B) split shell, (C) pressurized, (D) sealed construction, (E) environment resistant, and (K) fireproof.

As pointed out previously, there is an AN numbering system for identifying the connectors. For example, a connector may be identified as consisting of an AN 3106B-22-12S plug with an AN 3102-22-12P receptacle.

Table 6-1.—AN Connectors

AN type	Nomenclature
AN 3100	Wall-mounting receptacles.
AN 3101	Cable-connecting receptacles.
AN 3102	Box-mounting receptacles.
AN 3106	Straight plugs.
AN 3107	Quick-disconnect plugs.
AN 3108	90-degree angle plugs.
AND 10066	Integral-mounting receptacles.
AND 10459	Integral-mounting plugs.

These identifying letters and numbers stand for the following:

AN.	AN nomenclature system
3106.	Specification number for plug (straight plug)
3102.	Specification number for receptacle (box receptacle)
B.	Shell design (split type)
22	Size of the shell
12	Insert arrangement
P.	Pin contacts
S.	Socket contacts

Occasionally it may be necessary for you to fabricate a cable using AN connectors. The type of connector to be used will be specified in the maintenance manual for the particular equipment.

COAXIAL CABLES AND CONNECTORS.—Flexible coaxial cables (sometimes called RF cables) are a special type of cable used for carrying video and RF signals, cathode-ray-tube sweep currents and voltages, trigger range marks, blanking pulses, and other signals of radar receivers, transmitters, and indicators. These cables are constructed with special considerations for shielding, impedance, capacitance, and attenuation. All of these factors are of importance in many circuits. Coaxial cables have neither induction nor radiation losses. These lines have low attenuation even at very high frequencies, and are used at frequencies as high as 3,000 mcps.

The name coaxial is derived from the construction, in that the inner and outer conductors have a common axis. These cables consist of an inner conductor, a dielectric insulator, an outer conductor, and an outer covering. The inner conductor is usually made of copper, either plain, tinned, or silver coated. The dielectric insulation is usually polyethylene, although other materials are used. The outer conductor is made of a single or double braid of either plain, tinned, or silver coated copper. The outer covering is made of a synthetic resin (vinyl), teflon tape, or chloroprene. This covering serves both as weatherproofing and protection from mechanical abuse.

Flexible coaxial cables are classified in four groups; namely, general purpose, high temperature, pulse, and special characreristics. The general-purpose cables consist of various sizes of cables as just described. The high temperature cables are basically the same but usually have a dielectric made of teflon, and the outer covering is made of teflon tape and fiber glass braid which enables it to withstand high temperatures. Pulse cables have the ability to withstand high voltages because of conductor spacing and the type of dielectric used in their construction.

The special characteristics cables are made of various materials and sizes of inner conductor, outer conductor, dielectric, and outer covering. By varying these parts the capacitance, impedance, shielding, attenuation, voltage rating, and the ability to withstand weather and abuse are varied to fit special requirements. With exception of the special characteristics

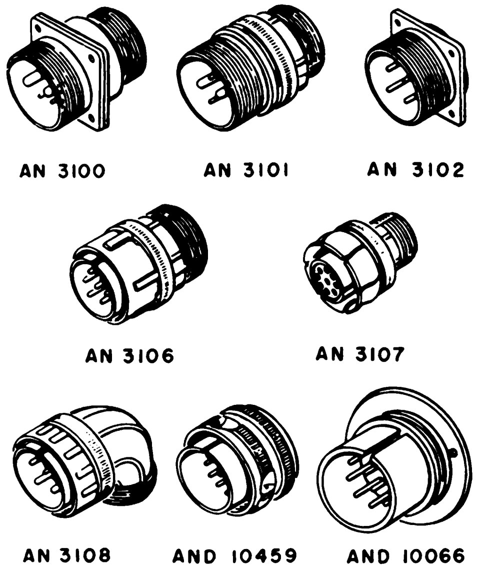


Figure 6-43.—AN connector shells.

type, these coaxial cables have an impedance in the order of 50 to 75 ohms. The impedance of the special characteristics type is often much higher. An example is the RG-65A/U which has an approximate impedance of 950 ohms and is used as a high impedance VIDEO cable. In replacing a coaxial cable, care should be exercised to use the correct replacement. Otherwise most of the advantages of coaxial cables are lost.

At frequencies near 3,000 mc., flexible coaxial cables have appreciable losses. At these frequencies rigid coaxial cables are used with air as the dielectric. The inner conductor is supported by ceramic or polystyrene beads.

Coaxial connectors may be divided into seven series (BNC, N, C, HN, LC, pulse, and twin). Each series consists of plugs, panel jacks, receptacles, straight and right angle adapters. The BNC series are small, lightweight, quick-connect and quick-disconnect types used with small RF cables. The N series are the general-purpose screw-lock connectors. The C types are similar to the N series in that they are used with medium sized cables but have the quick-disconnect featurer. HN types are high voltage connectors for use with medium sized cables while the LC series are large connectors. The pulse series are widely used in naval equipment. They are used with high voltage pulse cables, such as the modulator-to-transmitter pulse cable, in some older fire control radars. The twin series are used with cables that carry UHF, and are sometimes called UHF connectors.

STUFFING TUBES AND KICKPIPES

Two classes of stuffing tubes are illustrated in figure 6-44. The class shown in part A is designed to be installed in the wall of an electrical appliance or fitting to permit the insertion of an electric cable. The cable is terminated in the appliance. The class shown in part B is designed to be installed in a deck, bulkhead, or hull to permit an electric cable to be passed through the structure. The cable is not terminated after passing through the tube but continues to some distant point.

Both classes of stuffing tubes are forms of packing glands and serve a common purpose in preventing the passage of liquids and gases at the point of cable entrance.

A kickpipe is a pipe used to pass cables through decks wherever cable protection from mechanical injury is needed. The minimum length of a kickpipe is nine inches and the maximum length depends on the requirements. If the length of the kickpipe is over twelve inches, the top of the kickpipe is secured by a brace.

More recently nylon stuffing tubes have been developed by the Bureau of Ships. These stuffing tubes (fig. 6-45) are extremely durable and will be used where practicable when the present supply of metal stuffing tubes is exhausted.

Specific information on the installation of stuffing tubes and kickpipes is included in chapter 8 of the Electronics Installation Practices Manual, NavShips 900,171.

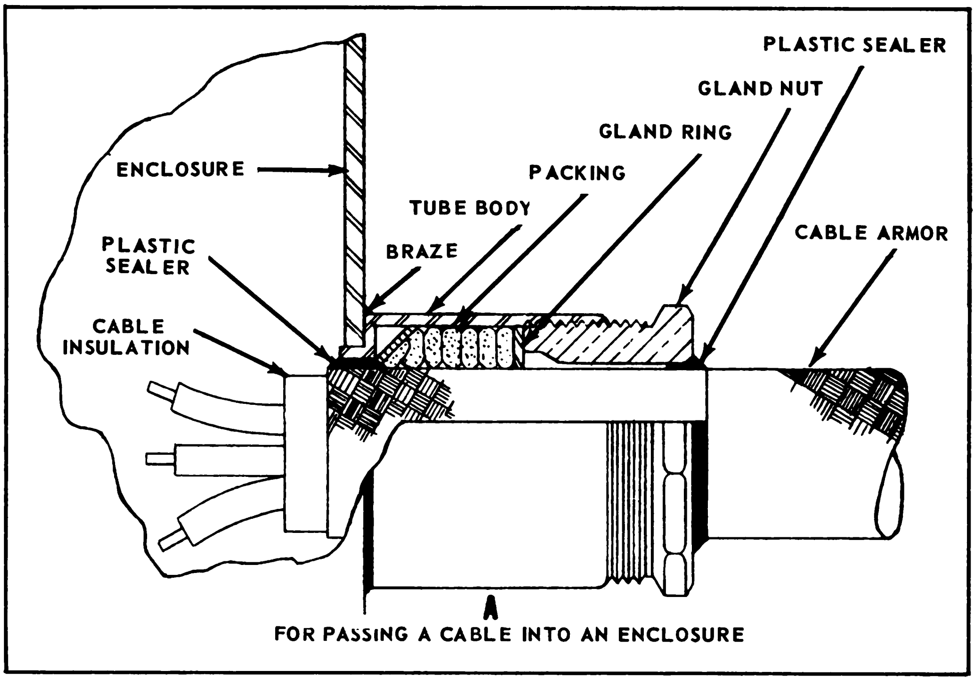
LAMPS

Lamps are devices that are used as sources of artificial light. They provide illumination for reading dials and to indicate the operational status of equipment, such as the mode of operation of a radar.

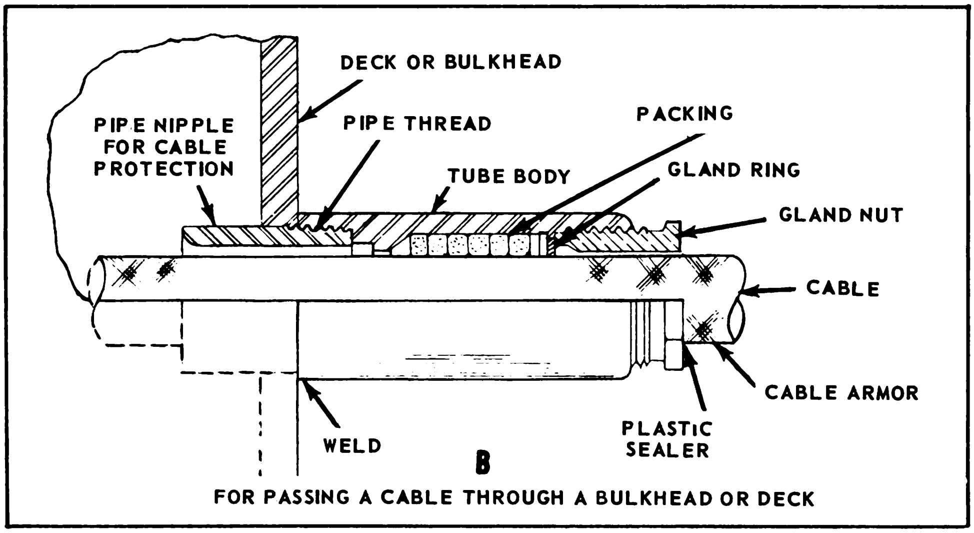
Lamps are a part of a light assembly. Generally speaking, a light assembly consists of a housing (fixture), a lamp, and a lens.

The parts of a lamp are the bulb, filament, and base. Incandescent lamps vary chiefly in ELECTRICAL RATING, BASE TYPE, BULB SHAPE, and BULB FINISH.

The ELECTRICAL RATING is usually expressed as combinations of the following items: volts, watts, amperes, and candlepower. (Candlepower is the luminous intensity expressed in candles and used to specify the



FOR PASSING A CABLE INTO AN ENCLOSURE



FOR PASSING A CABLE THROUGH A BULKHEAD OR DECK

12.77

Figure 6-44.—Types of stuffing tubes.

strength of a light source.) The lamp rating is marked on either the base or the bulb of the lamp. In the case of small lamps, the electrical rating is usually replaced by an identifying number.

The BASE TYPES vary as to size, number of electrical contacts, and the method of securing in a socket. The most common bases are the single or double contact bayonet (push in and turn) type. These are desirable for shipboard use since they lock in the socket and do not become loose because of vibration. The single contact is used in single-wire systems. In this system one side of the lamp filament is soldered to the base and the other to the contact. The double contact is used where the single-wire system is not practicable. In this system the filament is connected to the contacts and does not make an electrical connection to the base. Double contact bases are also used for dual filament lamps. The single and double contact type lamps cannot be used interchangeably.

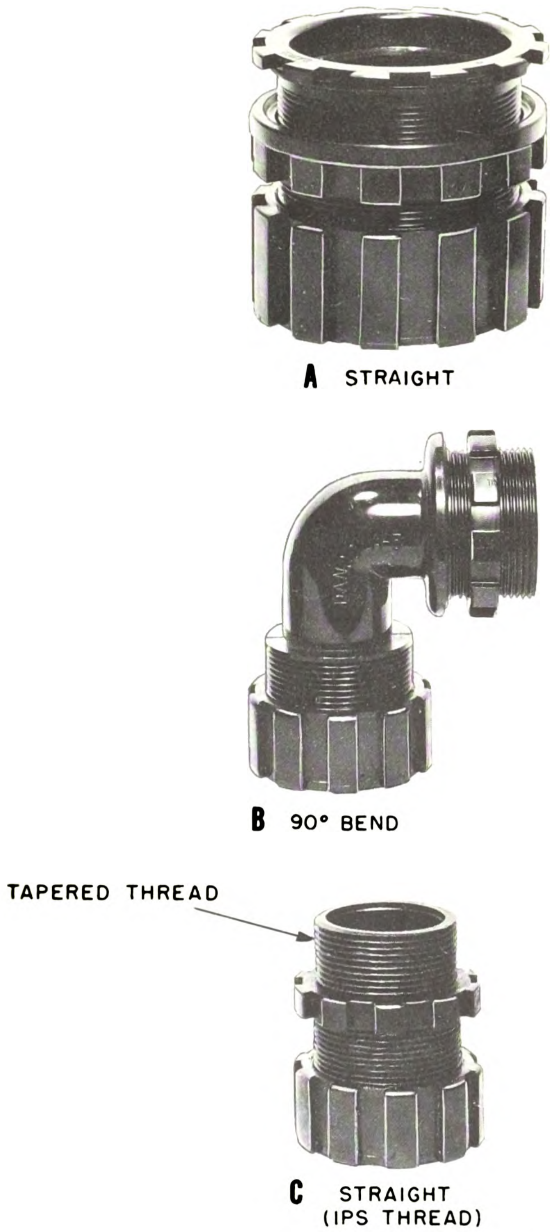
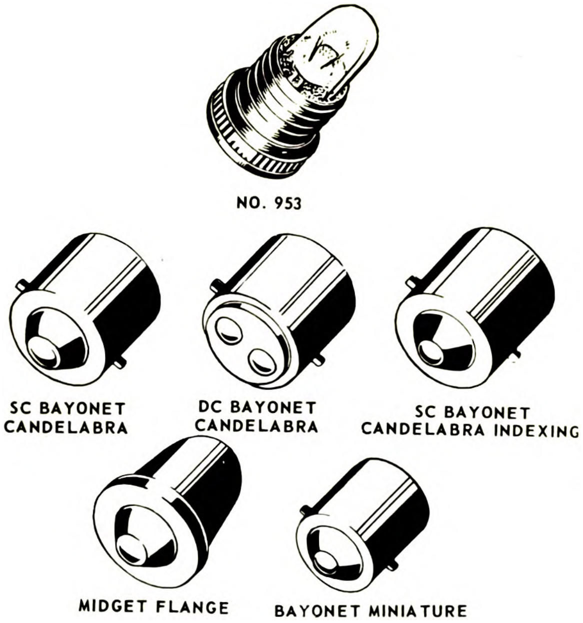


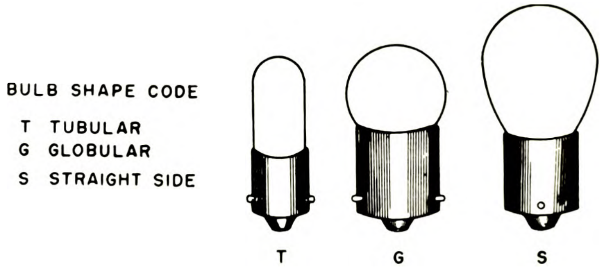
Figure 6-45.—Nylon stuffing tubes. 12.78

Some bases are of the screw type but they find limited use because they loosen easily. Figure 6-46 shows some of the popular types and sizes of lamp bases.

The sizes of lamp bases are classified by the following terms: miniature, candelabra, intermediate, medium, and mogul. The smaller sizes (miniature and candelabra) are used extensively in instrument panel lighting.



12.79
Figure 6-46.—Lamp bases.



12.80
Figure 6-47.—Common bulb shapes.

BULB SHAPES are designated by the combination of a letter and a numeral. The letter designation indicates the shape of the bulb in accordance with a code, and the number is a measure of the approximate maximum diameter of the bulb in eighths of an inch. The shapes of the more common glass envelopes are as follows:

"G"—globular
"T"—tubular
"S"—straight side
"PAR"—parabolic

For example, a bulb designated as T-6 has a tubular shape and a diameter of 3/4 inch. Figure 6-47 shows some of the more common bulb shapes.

CHAPTER 7

SYNCHROS AND DATA TRANSMISSION CIRCUITS

INTRODUCTION

It takes a lot of information to solve the fire control problem. This information must be sent back and forth between equipments located at a distance from each other. For example, a computer needs own ship's course, own ship's speed, and target range, bearing, and elevation, to solve the fire control problem. Own ship's course comes from the master gyro compass. Own ship's speed comes from the pitometer log. And target bearing, elevation, and range come from a director or radar set. All of these basic quantities are supplied by equipment located at distances of a few feet to possibly several hundred feet from the computer. Therefore, some sort of data transmission system is needed.

Fire control information is transmitted electrically between distant stations by synchro systems. The Mk 1A computer, which is a typical computer in this respect, has 40-odd synchros to receive and to transmit the data necessary for its operation. Obviously, a thorough knowledge of synchros and their circuits is necessary for the FT. The groundwork has been laid in Basic Electricity, NavPers 10086-A. The construction and theory of operation of various synchros are covered in the basic test; we will not repeat that information here. It is advisable to review the basic text before studying this chapter. Here we will present additional information that is not included in the basic course.

TYPES OF SYNCHROS

Before we cover the types of synchros, we will briefly summarize their common features and characteristics. Synchros are basically transformers. Various types have been developed to serve several different purposes. They are usually position-sensing devices which have the following things in common.

1. They operate on a transformer principle.
2. They have a "Y" connected stator. (Three windings 120° apart, each with a common connection. These three windings correspond to one of the windings of a transformer.)
3. They have a rotor winding. (A rotating winding which corresponds to the other winding of a transformer.)

Synchros sense position in one of three ways:

1. The position of the rotor in relation to a reference point (mechanical information).
2. The voltage on the stator winding in relation to a predetermined reference voltage (electrical information).
3. The voltage on the rotor winding in relation to a predetermined reference voltage (electrical information).

As you know, torque transmitters and receivers are energized with alternating current at their R1-R2 leads. The turns ratio between rotor and stator is such that a MAXIMUM of 52 volts for 115-volt units or 6.8 volts for 26-volt units is produced in any one stator winding.

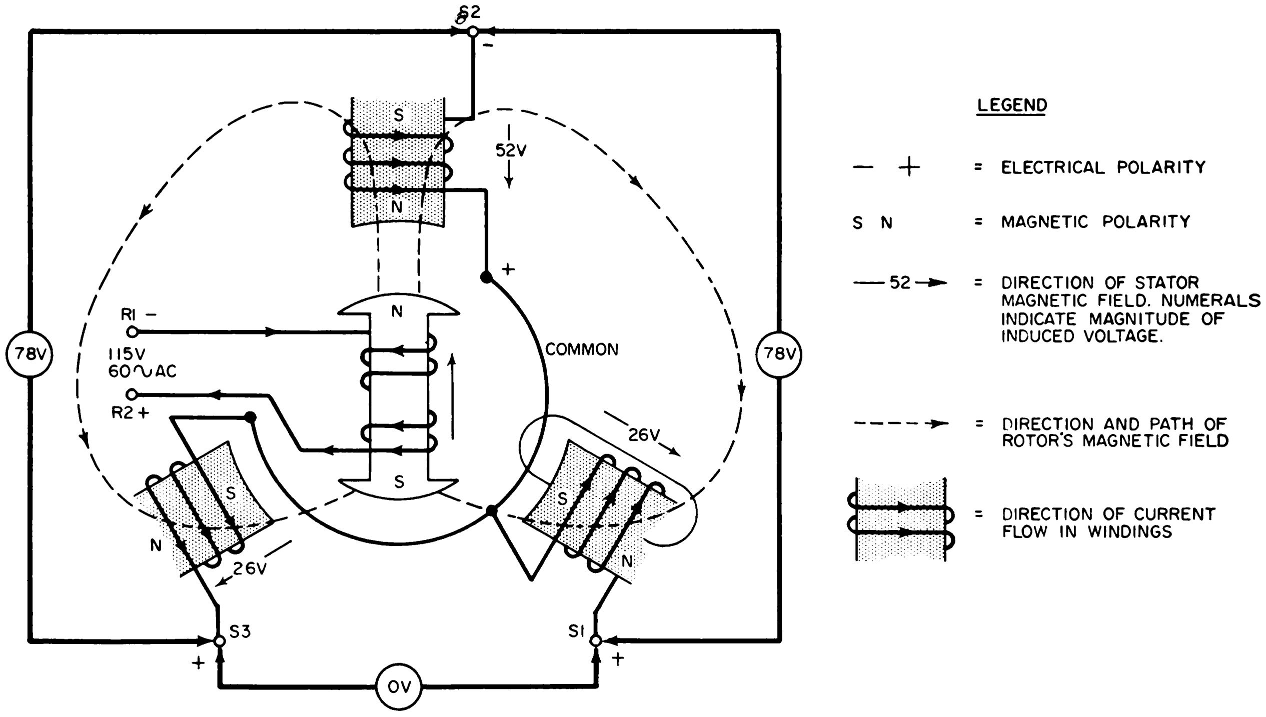
Figure 7-1 shows a synchro, either a torque transmitter or receiver, with 115 volts a-c applied to its rotor. The synchro is shown with a rotor angle of zero degrees. Rotor angle is measured from the longitudinal axis of the rotor to the axis through the center of the S2 winding. The axis of the S2 winding is the standard reference point, and it's called the ELECTRICAL ZERO point. All rotor angles are measured from this reference. The voltages on the stator windings at this position of the rotor are the reference values.

CLASSIFICATION OF SYNCHROS

We can classify the more common types of synchros by their function, size, and the supply

Table 7-1.—Synchro Functional Classifications

Functional Classification	Military Abbreviations	Input	Output
Torque Transmitter	TX	Rotor positioned mechanically or manually by information to be transmitted	Electrical output from stator identifying rotor position supplied to torque receiver, torque differential transmitter, or torque differential receiver
Control Transformer	CX	Same as TX	Electrical output same as TX but supplied only to control transformer or control differential transmitter
Torque Differential Transmitter	TDX	TX output applied to stator; rotor positioned according to amount data from TX must be modified	Electric output from rotor (representing angle equal to algebraic sum or difference of rotor position angle and angular data from TX) supplied to torque receivers, another TDX, or a torque differential receiver
Control Differential Transmitter	CDX	Same as TDX but data usually supplied by CX	Same as TDX but supplied only to control transformer or another CDX
Torque Receiver	TR	Electrical angular position data from TX or TDX supplied to stator	Rotor assumes position determined by electrical input supplied
Torque Differential Receiver	TDR	Electrical data supplied from two TDX's, two TX's or one TX and one TDX (one connected to rotor, one to stator)	Rotor assumes position equal to algebraic sum or difference of two angular inputs
Control Transmitter	CT	Electrical data from CX or CDX applied to stator; rotor positioned mechanically or manually	Electrical output from rotor (proportional to sine of the difference between rotor angular position and electrical input angle)


S2
52V
S
N
R1 −
115V
60∿AC
R2 +
78V
78V
COMMON
26V
26V
S
N
S
N
S
N
S3
S1
+
+
OV
LEGEND
— + = ELECTRICAL POLARITY
S N = MAGNETIC POLARITY
—52→ = DIRECTION OF STATOR MAGNETIC FIELD. NUMERALS INDICATE MAGNITUDE OF INDUCED VOLTAGE.
- - - -→ = DIRECTION AND PATH OF ROTOR'S MAGNETIC FIELD
= DIRECTION OF CURRENT FLOW IN WINDINGS

12.166

Figure 7-1.—Synchro voltages, rotor at zero degrees.

voltage and frequency. As you know, synchros are part of a synchro system. The function of the system determines the type synchros in it. If the synchro system provides a mechanical output (torque), which does the actual positioning of a load, it is a torque system. If it provides an electrical output which is used to control the power that does the mechanical work, it is a control system. Hence synchros can be classified by the function they perform in the system. Table 7-1 lists the military abbreviation, inputs, and outputs of the more common functional classifications of synchros.

IDENTIFICATION OF SYNCHROS

Synchros you will most likely encounter in ordnance equipment can be grouped into two broad categories: military standard synchros and prestandard Navy synchros. Military standard synchros conform to specifications which are uniform throughout the Armed Services. New equipments use synchros of this type. Prestandard synchros were made to meet Navy, rather than service-wide, specifications. Each category has a designation code for identification.

Military Standard Designation Code

This designation code identifies standard synchros by their physical size, functional purpose, and supply voltage characteristics. We will use two standard synchro designations: 18TR6 and 16CTB4a, as examples to explain the code. The first two digits indicate the diameter of the synchro in tenths of an inch, or to the next higher tenth. Thus an actual dimension of 1.75 inches becomes 18. The first letter indicates the general function of the synchro and of the synchro system: C for control; T for torque.

The next letter indicates the specific function of the synchro, as follows:

LETTER	DEFINITION
D	Differential
R	Receiver
T	Transformer
X	Transmitter

The letter B following the preceding letters indicates that the synchro has a rotatable stator.

The number after the letters stands for the operating frequency:

6 for 60-cycle
4 for 400-cycle

The lower case letter is a modification designation. Successive modifications are in alphabetical order.

Thus, the 18TR6 is a torque receiver with a 60-cycle supply voltage and a diameter of between 1.71 and 1.80 inches. The 16CTB4a is a control transformer for use in a 400-cycle system. It has a rotatable stator, and a diameter between 1.51 and 1.60 inches. The lower case "a" indicates that the synchro has been modified once.

Type designations for all standard synchros are assigned by this code. Synchros for use in circuits supplied by 26 volts are classified in the same way, except that the symbol 26V is prefixed to the designator. Otherwise, a 115-v source is assumed for the synchro system. Note that in table 7-1 only the functional designator is given. This is often the practice in OPs and in schematic diagrams. The complete identification is normally given in the physical description section of the OP.

Navy Prestandard Designation Code

This code identifies prestandard synchros as to their size and function by a number and letter combination. An example of a synchro identified by this code is a 5DG. synchro. Unlike the standard code, the number does not directly indicate the diameter of the synchro. The number indicates relative size of the synchro. The size increases with the number. The letters indicate the function, mounting, or special characteristics as follows:

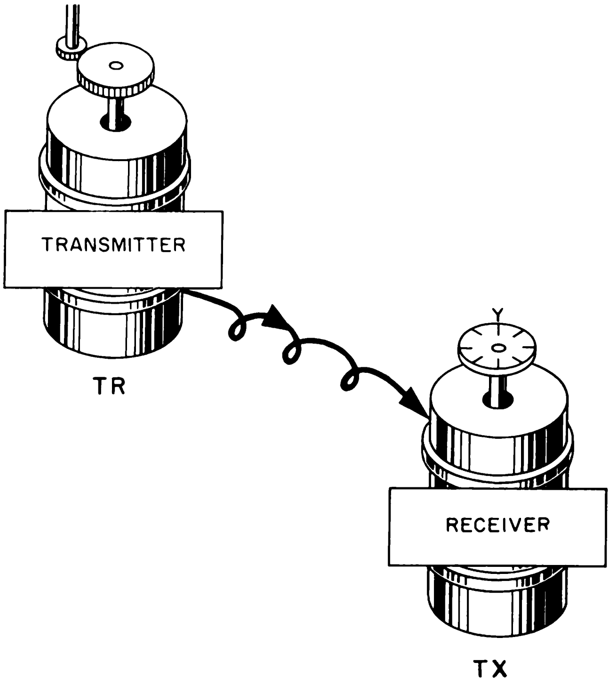
Letter	Definition
G	Transmitter
F	Flange mounted receiver, this letter is normally omitted if letters other than H or S occur in type designation.
D	Differential Receiver
DG	Differential Transmitter
CT	Control Transformer
H	High Speed Unit
B	Bearing Mounted Unit
N	Nozzle Mounted Unit
S	Special Unit

In some texts synchro transmitters, TX, are called generators, and receivers, TR, are called motors.

SYNCHRO ALIGNMENT

The primary function of a synchro system is to transmit information between remote units. The information is represented in the synchro transmission circuits as electrical potentials and currents which vary with the angular position of the transmitter's and the receiver's rotor as measured with respect to their stators. We can say then that the information as represented by electrical values in the circuits is in fact a measure of the angular displacement of the rotor from a reference point established by the stator. Hence, as previously mentioned, a synchro is basically a position-sensing device. Therefore, to receive the transmitted information correctly there must be a reference point common to both synchros and a common unit of measure used in both instruments.

To clarify this we will use a simple torque system (fig. 7-2). The TX rotor is coupled to a gear train and thus is mechanically restrained; its stator is stationary in its mounting. The



12.156
Figure 7-2.—Elementary synchro system.

TR rotor is free to turn; its stator, however, is stationary in its mounting. As you know, the axis of the S2 coil is the mechanical and electrical zero reference position of a synchro. Hence we have a common point within the synchros from which the angular displacement of the rotors can be measured. But if the synchro system is to transmit a quantity properly it must be interaligned with the instruments. In the system in the figure, this means that when we place the TX's dial on zero, which represents the value of the quantity in the instrument, the synchro must be at its zero position. Plainly the same is true for the TR and the receiving instrument; when the synchro is on zero, the dial should read zero. If the dials are identical you can see that the synchros are aligned to identical reference points. This is true although the receiver's reference is at some distance from the transmitter's. When these relationships have been established, the quantity on the TX dial can be transmitted correctly between the instruments by the synchro system.

Whatever the synchro system, either torque or control, the mechanical and electrical reference points must be aligned. All synchros can be considered fundamentally as transducers, in that they convert the input from an electrical signal to a mechanical signal, or vice versa. The input and output signals of a CT are electrical; but remember that its rotor is positioned mechanically. A review of the operation of synchro differentials, TDX and TRX, will show that they also are transducers. The point we wish to make clear is that the electrical alignment of synchros must be correlated with their mechanical alignment.

MECHANICAL ALIGNMENT

We are concerned here with the mechanical alignment of a synchro system with the quantity to be transmitted as it is represented in the transmitting instrument and with the quantity as delivered by synchro to the receiving instrument. Since these instruments are usually located at a distance from each other, the synchros are aligned individually to common reference lines.

To align a synchro system, the first step is to establish the reference lines so that they coincide, or are parallel. This is the mechanical alignment. As previously mentioned, the electrical axis of the S2 winding of a synchro is the reference line from which the rotation of its rotor is measured. Thus a synchro has a built-in reference line. The position of the S2 winding is the connecting link between the mechanical alignment of a synchro with the instrument, and the electrical alignment of the synchro system.

The synchro's mechanical input is assigned a reference value or position for alignment purposes. This value is normally the zero position of the quantity in the instrument. Some quantities, however, are assigned an arbitrary value as a reference point for alignment. Examples of quantities with reference points other than zero are: the reference for sight angle, level, and cross level is 2000 minutes; for range it is 10,000 yards, and for fuze setting it is 10 seconds, and for sight deflection it is 500 mils.

We now have established two reference lines, one in the synchro and the other in the instrument. If we place the mechanical input (or output) of the synchro at its reference value we can say that the two reference lines are coincident if the synchro rotor is at its electrical zero position. Let's see why this is true. Any quantity which can be made to vary linearly with the angular motion of the synchro rotor can be transmitted by a synchro system. (It does not matter that a quantity is basically linear, such as range and speed; as long as a change in the quantity will change the synchro rotor position a proportional amount it can be transmitted by synchro.) Thus if the input is at zero and the synchro rotor is at zero the reference lines are coincident.

If the synchro rotor is not at the electrical zero position, the synchro must be adjusted. (We will cover the electrical zero of a synchro next.) This is done by physically moving the synchro stator in its mounting or by adjusting the rotor by its mechanical input.

ELECTRICAL ZERO

In the Basic Electricity text we considered the terminal voltages of a synchro to explain synchro operation. From this study we have established the fact that for any given rotor position there is a definite set of stator voltages. Each type of synchro has a combination of rotor position and stator voltages which is called its electrical zero. The electrical zero condition is the reference point for the alignment of the synchro. We have defined the electrical zero in a torque system as the condition in which the axis of the rotor is lined up with the axis of the S2 winding. Look back at figure 7-1. In this illustration you can see that two such positions 180° apart are possible. As shown in the diagram, the rotor is at the electrical zero position, but if it were turned 180° we could still say it is lined up with the S2 winding. Let's see what is the electrical difference between these two rotor positions, and expand our definition of electrical zero.

In both the 0° position and the 180° position, the terminal voltage between S1 and S3 is zero. However, in the 0° position the voltages from S2 to S3 or from S2 to S1 are IN PHASE with the voltage from R1 to R2, while in the 180° rotor position the voltage from S2 to S3 (or S1) is 180° out of phase with the rotor voltage.

The electrical zero position is therefore completely defined as the position of the rotor in which the voltage between S1 and S3 is zero, and the voltage from S2 to S3 (or S1) is in phase with the voltge from R1 to R2.

Since there is a natural tendency to overlook or to assume the obvious, which in this case is the basic rules of electricity and magnetism used to explain synchro operation, it will be helpful as an exercise to check the values in figure 7-1. To prove the electrical zero condition as represented by the values in the figure we will summarize the rules.

1. A resultant magnetic field must always oppose the inducing magnetic field, (Lenz's law). We can use this law to determine the direction of current flow in the stator windings.

2. With the direction of current flow known, the left-hand rule can be used to determine magnetic poles established in the stator.

3. Next we can use the formula

$$E_s = E_{max} \times \cos \theta$$

to determine the voltages induced in the stator windings. You should commit this formula to memory, for reasons that will become apparent when you take the examination for advancement in rating.

ELECTRICAL ZERO IN A CONTROL SYSTEM

The electrical zero position of the transmitter in a control system is identical to the TX or TR in a torque system. The receiver in the control system, CT, however, must be described in a different manner. As you know, the output of a CT is the voltage induced in the rotor from the stator. Hence the electrical zero of a CT can be defined as follows: With a set of voltages on the stator which represent the zero reference signal, the output of the rotor is minimum or null voltage. (Normally it is not possible to obtain an absolute zero output due to flux leakage. The leakage is slight and will not disturb the control system, but we will use null rather than zero to describe the electrical zero position.) At its electrical zero position, the axis of the CT rotor is at a right angle with the axis of the resultant stator field. As in the case of the TX, it is possible for the rotor of a CT to be 180° out and still obtain null voltage. The rotor is in the correct electrical zero position if, when the rotor is turned slightly in a counterclockwise direction, the voltage between R1 and R2 is in phase with the voltage between S2 and S1 or S3.

ZEROING PROCEDURE

The procedure used to adjust a synchro to its electrical zero position depends upon the tools you have and how the synchro is connected in the system. Each synchro is adjusted as an individual unit, but its interconnection with other units in the system must be considered. OP 1303 (First Revision) entitled, "United States Navy Synchros", covers methods for adjusting all types of synchros under various conditions. In this discussion we will cover the setting of synchros to electrical zero with a voltmeter.

One of the major considerations in zeroing a synchro is whether its rotor is free to turn or not. The OP covers separate methods for synchros with their rotors free to turn and for synchros with restrained rotors. The voltmeter method, however, can be used in either case. An electronic or precision voltmeter having a 0- to 250-volt and a o- to 5-volt range should be used. On the low scale the meter should be able to measure voltages as low as 0.1 volt.

There are two major steps in the zeroing procedure of a synchro. First, the coarse or approximate setting is determined, and, second, the fine setting is made. The coarse adjustment is a check between the correct setting and a setting 180° out. Recall from the discussion of electrical zero that the difference between the two positions determines the phase relation between the voltages on S2 to S1 (or S3) and on R1 and R2. The voltages are in phase when the rotor is at its electrical zero position, and 180° out of phase when the rotor position is 180° away from electrical zero. Hence the coarse check provides a means to determine the phase relation between the supply voltage and the induced voltages in the S2 and S1 stator windings. We will show you later exactly how this is done.

Standard synchros have an arrow stamped on the stator frame and a reference line scribed on the rotor shaft. With the synchro input on zero or the reference value, the alignment of the arrow and the line on the rotor will set the synchro on approximate zero. Thus, with standard synchros, this is the coarse check.

The alignment of a synchro system would logically start at the origin of the quantity being transmitted. For example, assume that you wish to align the synchro system which transmits director train. Naturally you would start at the director where this quantity originates. The first step in the alignment would be to set the director exactly on zero train. Next you would set the director's train transmitters on their electrical zero position. With the transmitters on zero you can now set each receiver to its electrical zero. Since director train is a basic quantity there will be many receivers in the system. But each receiver can be adjusted as an individual unit since the electrical zero position is common to the whole system.

With this much out of the way we can now get to the meat of the topic—how to zero the different types of synchros. Remember, there are alternate methods not covered here.

Zeroing a CX or TX

Control transmitters (CX) and torque transmitters (TX) are functionally and physically identical. Therefore, they are zeroed in the same manner. The zeroing procedure is broken down into steps as follows.

1. Carefully set the quantity whose position the CX or TX transmits in its zero or reference position. This should place the synchro at its electrical zero position.
2. Deenergize the synchro circuit and disconnect the stator leads. Set the voltmeter to its 0- to 250-volt scale and connect it into the synchro circuit as shown in figure 7-3A. Figure 7-3B shows the equivalent circuit. Many synchro systems are energized by individual switches. Hence the instrument may be off but the synchros energized. Be sure the synchro power is off before working on the connections.
3. Energize the synchro circuit and turn the stator or rotor until the meter reads about 37 volts (15 volts for 26-volt synchros). This is the coarse setting and positions the synchro approximately on electrical zero. While doing this step, check that the quantity has not moved off its reference position.
4. Deenergize the synchro circuit and connect the meter as shown in figure 7-4.
5. Energize the synchro circuit and adjust the rotor for null, or minimum voltage. The final voltage reading should be taken on the 0- to 5-volt scale of the meter. After the

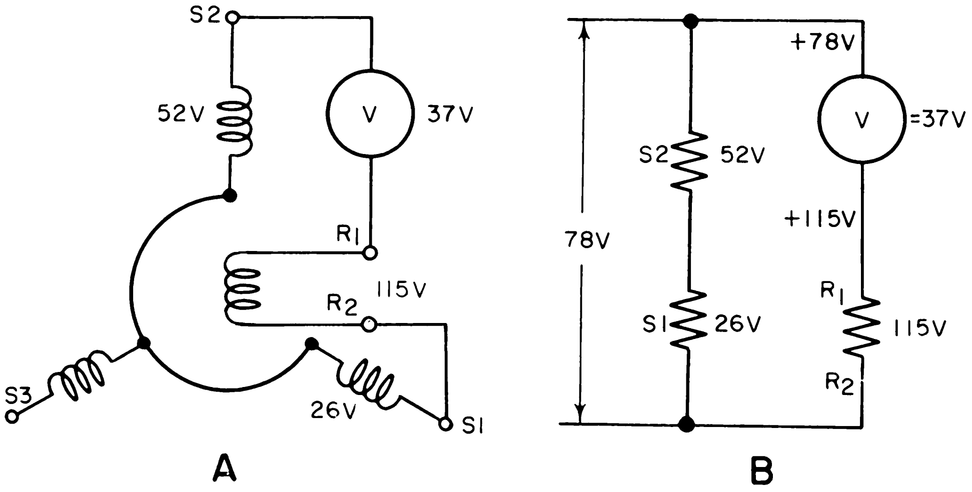


Figure 7-3.—Coarse zero check for a TX or CX.

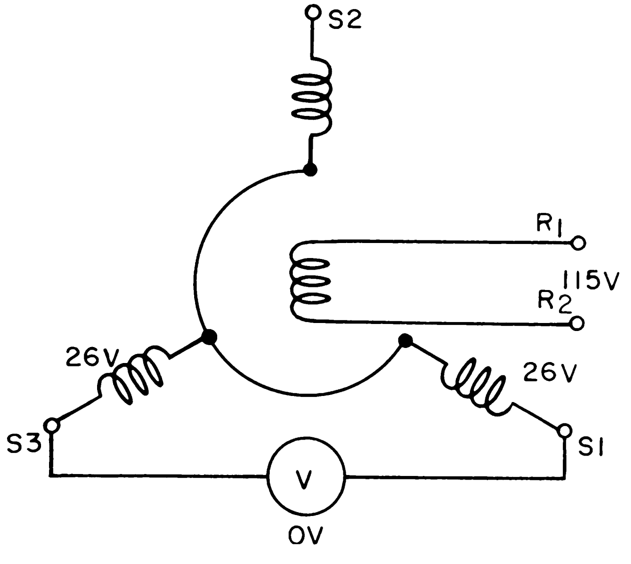
1.120.2

synchro has been set and the adjustment secured, recheck the quantity's position and the meter reading.

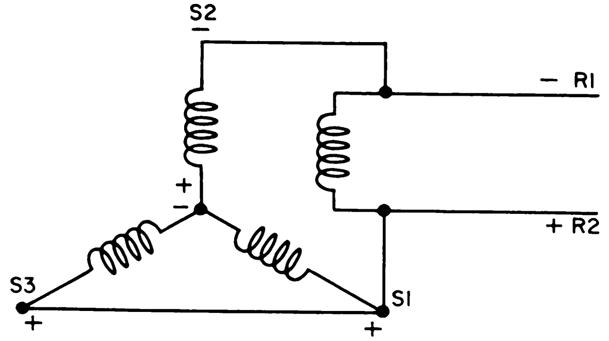
Zeroing a TR

In many installations a torque receiver, (TR), has a free rotor. A synchro with a free rotor can be zeroed by a simple method with no special equipment needed. This method, called an electric lock, requires only several short pieces of wire to be used as jumpers. Even they can be eliminated if the synchro leads are long enough. Essentially all you need is a source of electricity.

Figure 7-5 shows the synchro connections for an electric lock. S1 and S3 are connected together; therefore the voltage between them is zero. S1 and S3 are then connected to R2. S2 is jumped to R1; therefore both have the same phase. There is a similarity between the description of this method of zeroing a synchro and the definition of electrical zero. When power is applied to the synchro, the rotor will snap to the electrical zero position. Now you can align the dial, pointer, or any other device which is associated with the synchro, to its reference position. But do it quickly—take no longer than TWO minutes. Remember, the entire line voltage, 26 or 115 volts, is dropped across the stator windings, which are now in parallel with the rotor winding.



1.120.1
Figure 7-4.—Fine zero check for a TX or CX.



1.119A
Figure 7-5.—Connections for an electric lock.

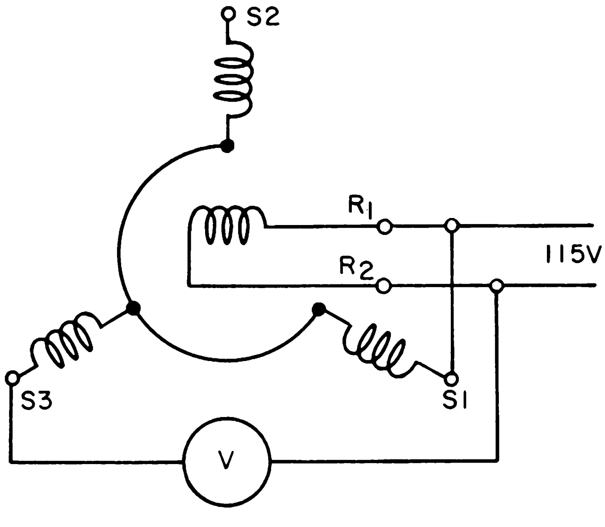
The electric lock can be used only with synchros whose rotor is free to turn. If the rotor is not free the voltmeter method, as described for the TX, may be used. A simple check on the common electrical zero position of a synchro system can be done with a jumper. Put the transmitter and receiver on zero and intermittently jumper S1 and S3 at the receiver. The receiver should not move. If it does the transmitter is not on zero and should be rechecked.

Zeroing a CT

The rotor of a control transformer, (CT), is not free to turn; therefore we will use the voltmeter method. The zeroing procedure is as follows:

1. Position the unit associated with the CT at its zero or reference position.
2. Remove the connections from the CT and reconnect as shown in figure 7-6.
3. Adjust the rotor or stator to obtain minimum voltage reading. This is the coarse check.
4. Reconnect the CT and meter as shown in figure 7-7 for the fine setting.
5. Adjust the CT for a minimum or null voltage reading. After the adjustment is secured, check to make sure the meter reading has not changed.

Here again, as in the electric lock procedure, the 115- or 26-v supply is dropped across the stator windings. Consequently there is the danger of overheating and permanent damage to the synchro if it is connected in this manner for more than two minutes. This danger can be avoided if a 78-v instead of 115-v, and a 10.2-v instead of 26-v supply is used. Unfortunately a



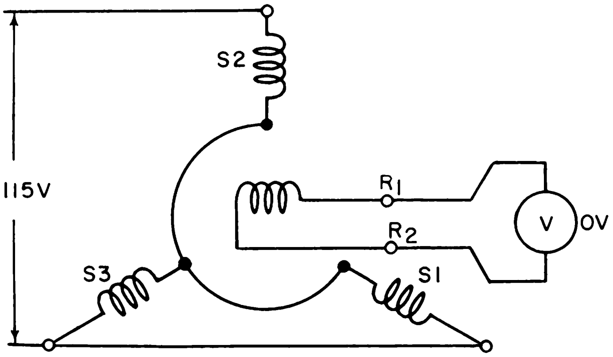
1.119—.123
Figure 7-6.—Coarse zero check for a CT.

78-v or 10.2-v supply is not usually obtainable on the job.

Electrical Zero for Differentials

A differential modifies the information in the synchro system. Therefore a differential is on zero if the information can pass through it without a change in value. In the electrical zero position the axes of the R2 and S2 windings coincide.

To zero a torque differential transmitter, (TDX), a control differential transmitter, (CDX), or a torque differential receiver, (TDR), using a voltmeter, proceed as follows.



1.120.1
Figure 7-7.—Fine zero check for a CT.

1. Set the quantity whose position the TDX or CDX transmits accurately in its zero or reference position.
2. Disconnect the differential, set the voltmeter on its 0- to 250-volt scale, and connect as shown in figure 7-8.
3. Turn the stator until the meter reading is minimum. The differential is now on approximate electrical zero. This is the coarse setting.
4. Reconnect as shown in figure 7-9 for the fine setting. Turn the stator until a null reading is obtained. The meter should be on the 0- to 5-volt scale for the null voltage reading. Secure the stator and recheck the null voltage.

SYNCHRO CAPACITORS

When a synchro differential or a control transformer is connected to a transmitter, the

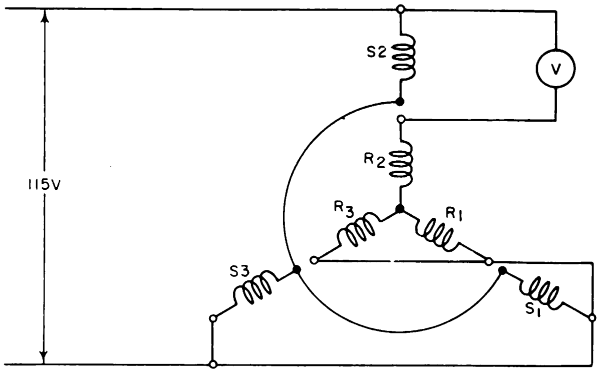


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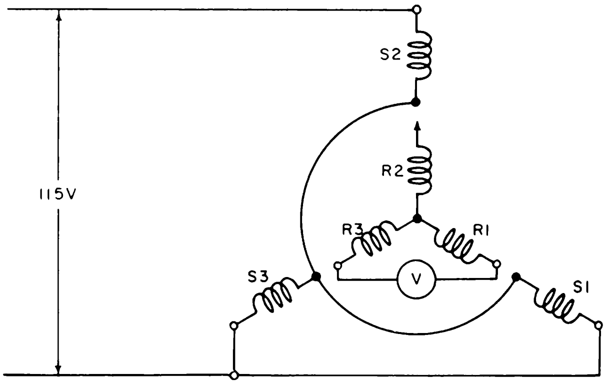
Figure 7-8.—Coarse zero check for TDX or CDX.



12.278
Figure 7-9.—Fine zero check for a TDX or CDX.

transmitter must supply the stator currents to the other synchro. Remember, the rotor of a differential or a control transformer is not energized by the line voltage. Therefore, their stator windings are inductive loads on the transmitter. In a-c circuits the current through a coil lags the applied voltage by an amount of time determined by the coil impedance. The effective power of a circuit in which the voltage and the current are out of phase is less than the volt-ampere product.

A capacitor connected across the coil will reduce the out-of-phase current in the circuit. If the capacitive reactance of the capacitor is equal to the inductive reactance of the coil, the two will cancel. The resultant current in the circuit would be determined solely by the d-c resistance of the coil winding.

A synchro capacitor bank consists of three equal delta-connected capacitors (fig. 7-10A). The capacitors are connected in parallel with the stator windings of a synchro differential or control transformer (fig. 7-10B). The stator currents drawn from the transmitter are reduced, and when the synchros are in correspondence the transmitter supplies only the current due to the windings' resistance.

The rotor of a torque receiver is energized by line voltage. Currents present in the stator circuits of a TX-TR synchro system are a result of a voltage difference between the stators. If the synchros are in correspondence there is no voltage difference and hence no current in the stator circuits. Therefore capacitors are not required in a TX-TR synchro system.

DUAL-SPEED SYNCHRO SYSTEM

Fire control systems are extremely accurate, but a system's accuracy can not be greater than the accuracy of any of its parts. A system's accuracy depends on the accuracy of its instruments and their associated data transmission systems. Therefore the accuracy of a synchro system which transmits data between instruments is important.

SYNCHRO ERRORS

A perfect synchro has never been made. Synchros will always contain some errors due to manufacturing inaccuracies and assembly. As you know, for every physical position of a synchro rotor there is a corresponding electrical position. For example, if you put the rotor of a perfect synchro transmitter at 30°, as shown in figure 7-11, the voltages you will read across the stator terminals will be as follows:

S1 to S2—90 volts and 180° out of phase with R1-R2.

S1 to S3—45 volts and in phase with R1-R2.

S2 to S3—45 volts and in phase with R1-R2. These stator voltages and phase relationships are unique for 30° rotor position. (See fig. 7-11B.) You won't get these quantities at any other position of the rotor. But, as we said before, synchros are not perfect. Any difference between the actual physical position of the

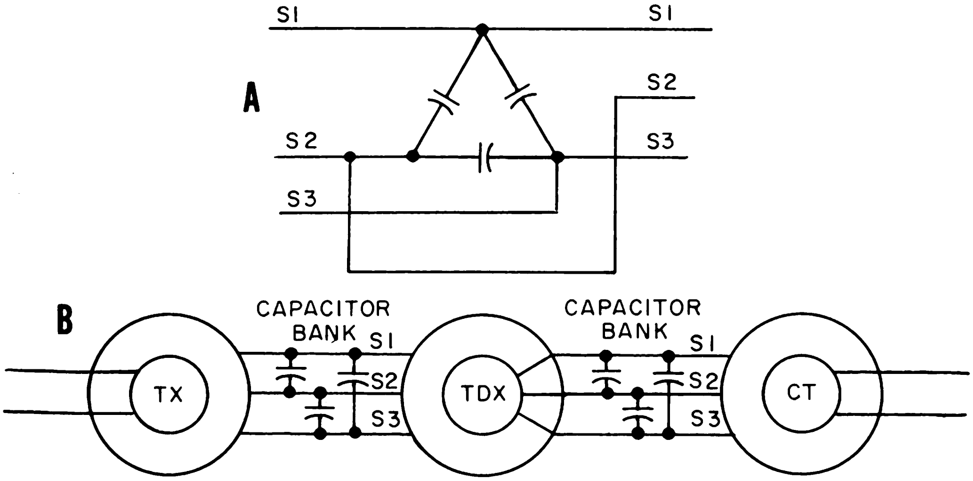


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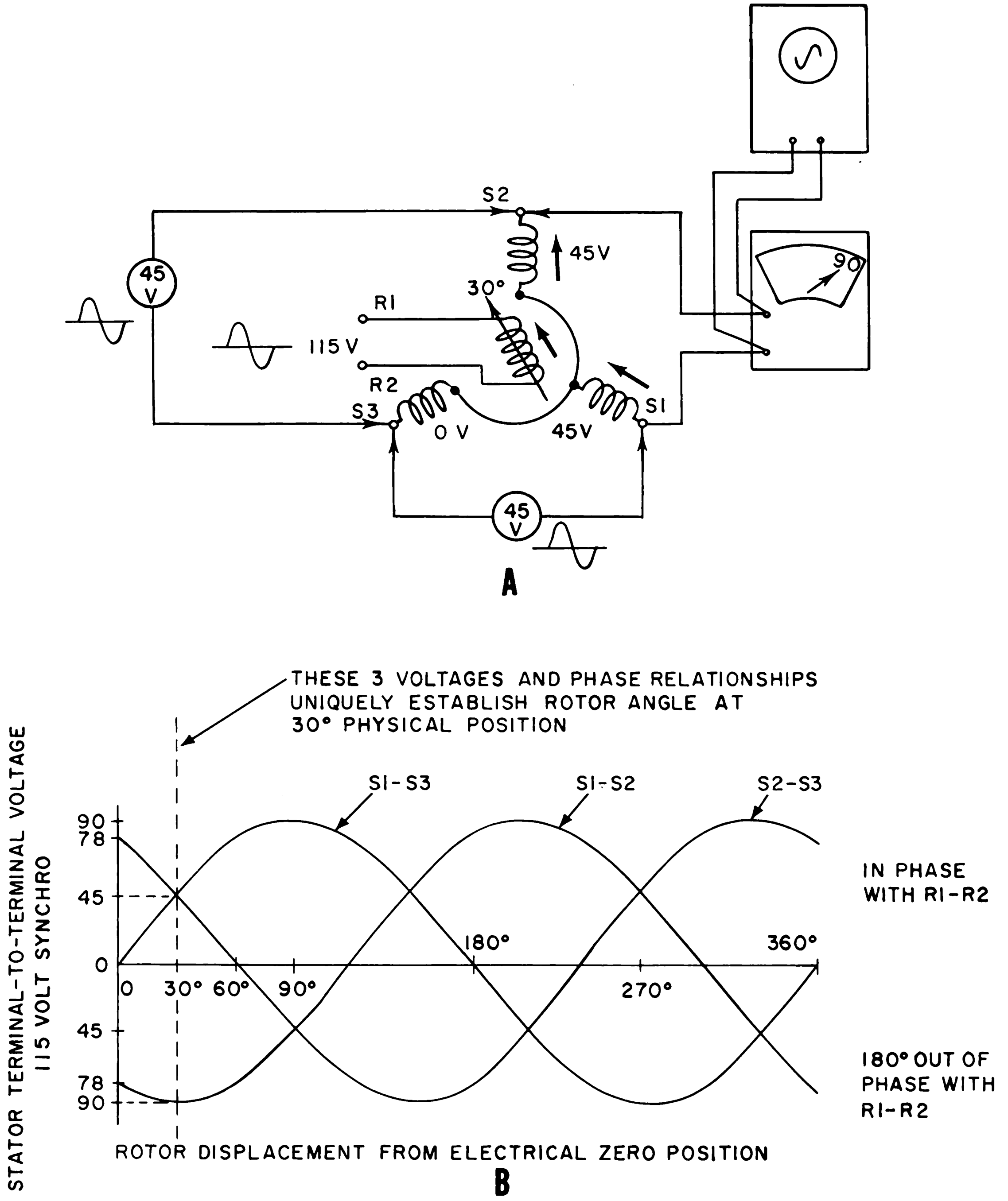
Figure 7-10.—Synchro capacitors.


S2
45V
30°
R1
115 V
R2
S3
0 V
45V
S1
45 V
45 V
90
A
THESE 3 VOLTAGES AND PHASE RELATIONSHIPS UNIQUELY ESTABLISH ROTOR ANGLE AT 30° PHYSICAL POSITION
S1-S3
S1-S2
S2-S3
STATOR TERMINAL-TO-TERMINAL VOLTAGE 115 VOLT SYNCHRO
90
78
45
0
45
78
90
0
30°
60°
90°
180°
270°
360°
IN PHASE WITH R1-R2
180° OUT OF PHASE WITH R1-R2
ROTOR DISPLACEMENT FROM ELECTRICAL ZERO POSITION
B

83.71

Figure 7-11.—Synchro electrical error.

rotor and the electrical position is known as electrical error. (Sometimes the electrical error is called static accuracy.) It is possible to get the voltage readings and phase relationships listed above when the rotor of a real synchro is at, say 30° and 18 minutes. Therefore, the synchro has an electrical error of 18 minutes. This is a typical error for a control transformer. The electrical error for synchro transmitters can be that high, but usually it is in the order of 8 to 15 minutes.

Consider a practical synchro system consisting of a control transformer and transmitter like the system shown in figure 7-12. If both units have an electrical error of 18 minutes, the total possible electrical error is 36 minutes, or a little over half a degree.

What can cause errors in synchros? Briefly, here are some of the causes:

1. It is impossible to make the three stator windings the same. Each winding could have a different number of turns, for example.

2. The rotor and stator assemblies must be exactly round. If they are slightly elliptical, an electrical error results.

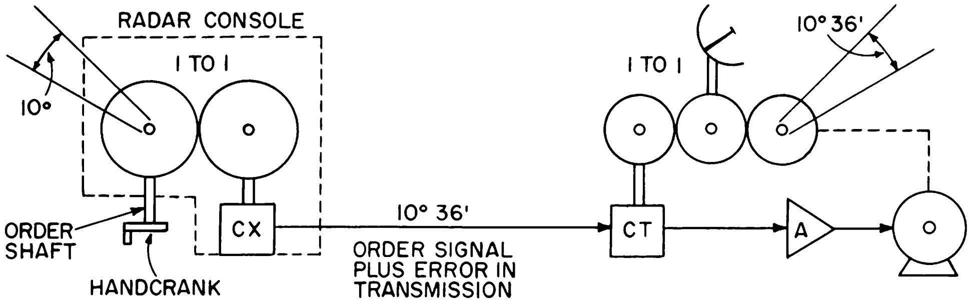
3. The rotor of a synchro must be put in the exact center of the stator bore. If the rotor is off center by just a small fraction of an inch, then there will be an electrical error.

A servo is only as accurate as its error detector. If there are electrical errors in the servo's data transmission system, the servo output will reflect the electrical error. Now let's see how electrical errors show up in a single synchro system.

The pictorial diagram in figure 7-13 shows a synchro transmitter and control transformer connected in the conventional way. We will assume it is a perfect system. It has no electrical error. Both units are perfect. Notice particularly that all gear ratios are 1:1. That is, if we turn the transmitter handcrank one revolution, the transmitter rotor will turn one revolution (360°). Similarly, if you turn the CT's handcrank one revolution, the control transformer rotor will turn one revolution. Furthermore, assume that the dials on both rotor gear faces are so accurate that we can read angular position of the respective rotor in minutes of arc as well as degrees of rotor angular position.

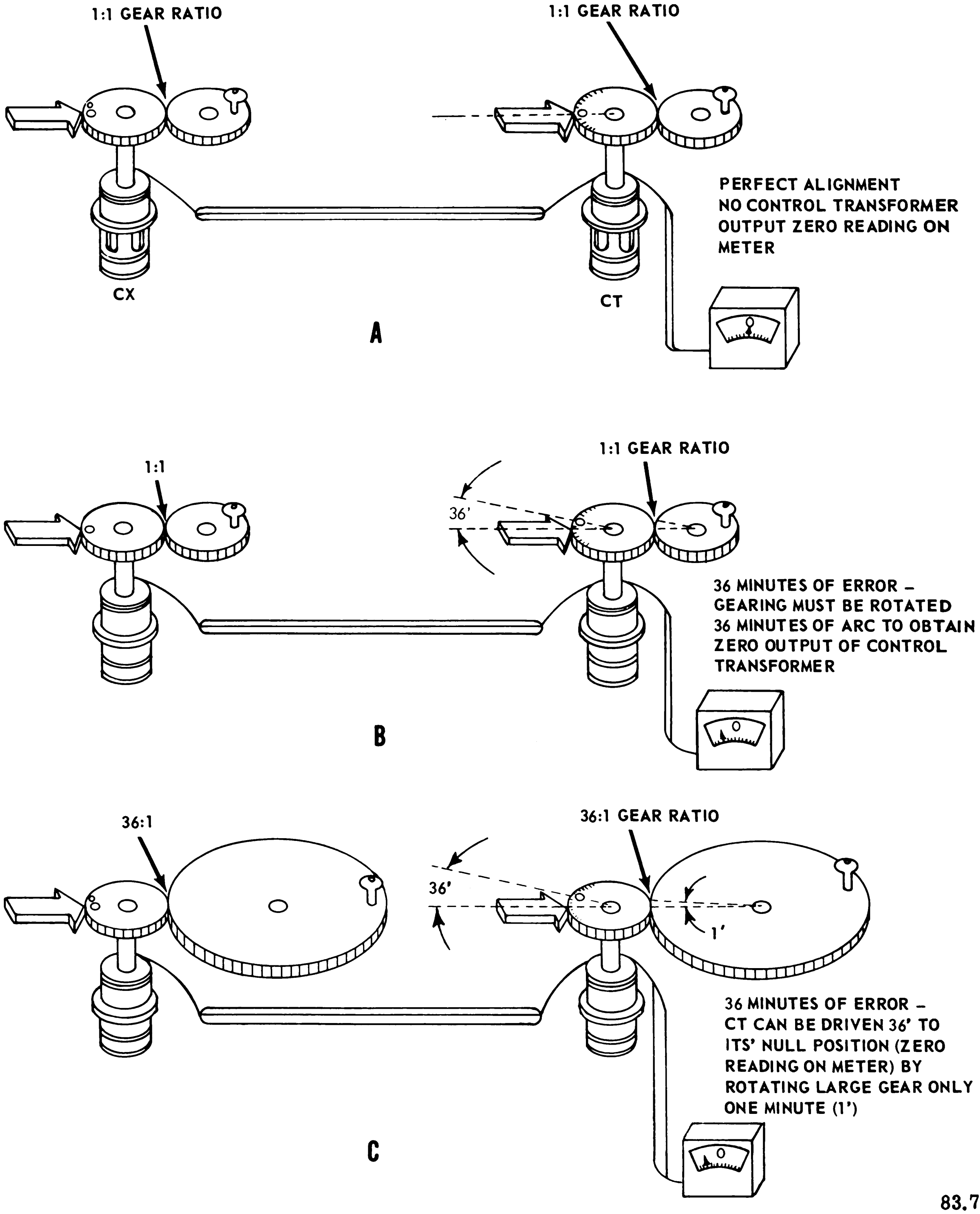
Since we have a perfect system, if we put the rotor of the transmitter on zero, and then turn the crank at the CT end of the system, a voltmeter connected across the CT R1-R2 leads will read zero when the CT dial reads zero. If we turn the rotor of the transmitter to 5°, as read on the CX rotor dial, and then turn the control transmitter handcrank until the voltmeter reads zero volts, a glance at the CT dial will show that it reads exactly 5 degrees. You can repeat this experiment for every position of the dial and the result will be that when the transmitter rotor is at a selected position, the CT rotor will be at the same position when the voltmeter reads zero. In other words, we have perfect transmission of data.

But now look what happens when we use actual synchro units in the system. Assume the synchro system contains an accumulated electrical error of, say, 36 minutes. The pictorial diagram in figure 7-13 shows the same setup as we had before. But instead of perfect synchros, we have replaced them with ones that have an electrical error of 18 minutes apiece. If we put the dial of the transmitter at zero, we will transmit what we think is an electrical signal proportional to zero degrees. But to get a null (minimum or zero reading of the voltmeter), the CT rotor must turn through an angle of 36 minutes. At null it is obvious that the two rotors are not in the same angular position. The transmitter rotor is at its zero position and the control transformer rotor is 36 minutes away from zero. Now turn back to figure 7-12. Assume that the data transmission system shown there



55.15

Figure 7-12.—Error in synchro transmission.



83.72

Figure 7-13.—Electrical error in a synchro system.

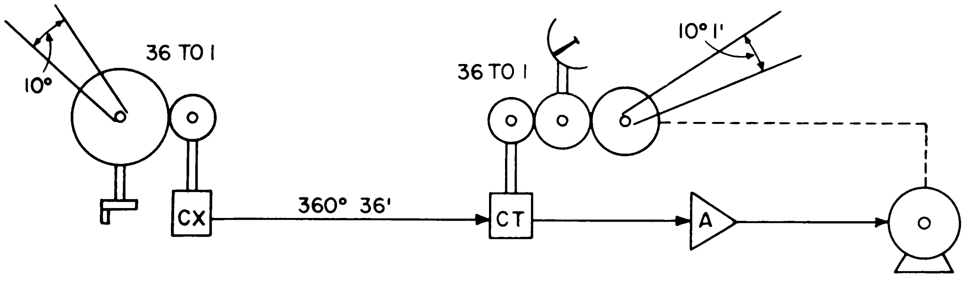
also has a 36 minute electrical error. If the radar operator turned the CX rotor shaft to the position corresponding to zero antenna elevation order, the power drive servo would position the antenna at zero degrees and 36 minutes. The antenna is certainly not at the ordered position. It is close to it, maybe, but it is not exactly on. For this reason the system we are talking about here is called a COARSE system. It transmits approximate angular position information because the system contains electrical error. But antenna power drives must receive very accurate aiming information so that the radar beam can be pointed in the right direction. Therefore, an additional synchro system, called the FINE system, is used along with the coarse system. To show how a fine system works we can make one out of the coarse system we've just talked about simply by changing gear ratios.

In figure 7-13 we have done just that. Instead of a 1:1 gear ratio between the synchro rotors and their handcranks we have installed gears with a ratio of 36:1. If we turn either handcrank one revolution, its associated rotor will turn 36 times. Also it follows that if we turn either crank one minute, then the rotor geared to the crank will turn through 36 minutes of arc. Now mentally place both dials at zero. Assume that we have a 36 minute electrical error in the synchro system. With the increased gear ratio, we only have to move the control transformer handcrank one minute to null the voltmeter even though we have a 36 minute error in the system. So, by increasing the gear ratio we have reduced the effect of the error 36 times. Remember, in an identical situation using a coarse (1:1 ratio) system we had to move the CT rotor 36 minutes to get system null.

In the preceding discussion about synchro system electrical error we manually turned the CT handcrank which moved the CT rotor until we saw a zero reading on the meter dial. Now let's replace the human operator with a servo and show how increased gear ratios improve the accuracy of the synchro system and its associated servo. The diagram in figure 7-14 shows an antenna power drive servo controlled by a fine synchro system. Assume there is a 36 minute accumulative error in the synchro system. If we put the input shaft (CX rotor shaft) at its ZERO physical position and the antenna at its zero position, the servo will drive the antenna through a ONE minute angle. But, because of the 36:1 stepped-up gear ratio between the antenna and the CT's rotor, the rotor of the CT will turn 36 minutes, cancelling out the 36 minute electrical error. At this point, the voltage at the amplifier input is zero, and the servo stops. The important point is that the antenna has moved only one minute even though the error in the synchro transmission system is 36 minutes. Or, you can say the angular position between the input and output of the system (data transmission system and servo) is one minute. If we had used a coarse transmission system with a 1:1 gear ratio, the difference between the input shaft and the output shaft would have been 36 minutes when the servo stopped driving the antenna.

DISADVANTAGES OF 36:1 SYNCHRO TRANSMISSION

The main disadvantage of the 36:1 transmission is that the servo is no longer self-synchronous. In the 1:1 transmission system the output shaft is synchronized with the input shaft at only one point. In other words, there is only one position the output shaft can assume which will allow correspondence between the rotors of



55.16

Figure 7-14.—Decreasing synchro transmission error by increasing gear ratio.

the CT and the transmitter. However, in the 36:1 transmission system the output shaft can be in correspondence at 36 different positions for any one position of the input shaft. For example, if the rotor of the transmitter is at 0° (see fig. 7-14), the output shaft, and consequently the antenna, could be synchronized at 0°, at 10°, at 20°, and so on, in steps of 10 degrees. In each of these positions of the output shaft, the control transformer's output is zero, thus bringing the CT into false correspondence with the transmitter in each case.

COMBINING THE FINE AND COARSE SYSTEMS

Although the fine system provides high accuracy in a power drive servo, it is seldom used by itself since, as you have seen, it does not provide true synchronization of the input and output at all times. We certainly would not want the antenna pointed at 80 degrees, when the synchro transmitter rotor shaft was at, say, 10 degrees. Therefore, the fine system is always combined with a coarse system. The fine synchro system provides a very sensitive control at times when the error between the order signal and the servo output is small. Since this is a 36-speed synchro, however, it can bring the antenna to any one of 36 positions. It is the job of the coarse synchro system to bring the antenna close enough to the true synchronous position so that it is within the range of the fine synchro.

ZEROING DUAL-SPEED SYNCHRO SYSTEMS

If a fine and a coarse synchro are used to define a quantity's position, the synchros must be zeroed together. As pointed out earlier, the coarse synchro will define the position of a quantity to within the range of the fine synchro's capability to define the position more precisely. From this you can reason that the coarse synchro provides the first significant figure in the numerical description of the quantity's position. Obviously then the coarse synchro is zeroed first. When zeroing the synchros in a system you can consider each synchro as an individual unit. Thus one of the methods already described can be used to zero the coarse synchro.

The next step after the coarse synchro is zeroed is to zero the fine synchro. A fine synchro provides the next significant figure in the numerical description of the quantity's position. The fine synchro is zeroed as an individual unit. But the quantity's zero or reference position has already been established with respect to the coarse synchro's electrical zero position. Hence when you zero a fine synchro the setting of the coarse synchro and the quantity must be set together.

There are a few three-speed synchro systems. These systems are zeroed in the same manner as the dual-speed systems. First, establish the zero position for the synchro which provides the most significant figure, and work down to the least significant figure. Just remember that all the synchros in a system must have a common electrical zero position.

If the synchros in a dual-speed system do not have a common zero position, there is a definite possibility that the system will not synchronize properly. This is not hard to visualize. For example, assume that the director train receivers in the computer are not zeroed together. The coarse synchro would drive the director train system to its zero position. Since, however, this position is not the fine synchro's zero position it would drive director train to its zero position. Hence the two receivers would buck and the director train in the computer would oscillate between the two zero positions.

The fact that the receivers in a synchro system are zeroed together leads us into the next subject.

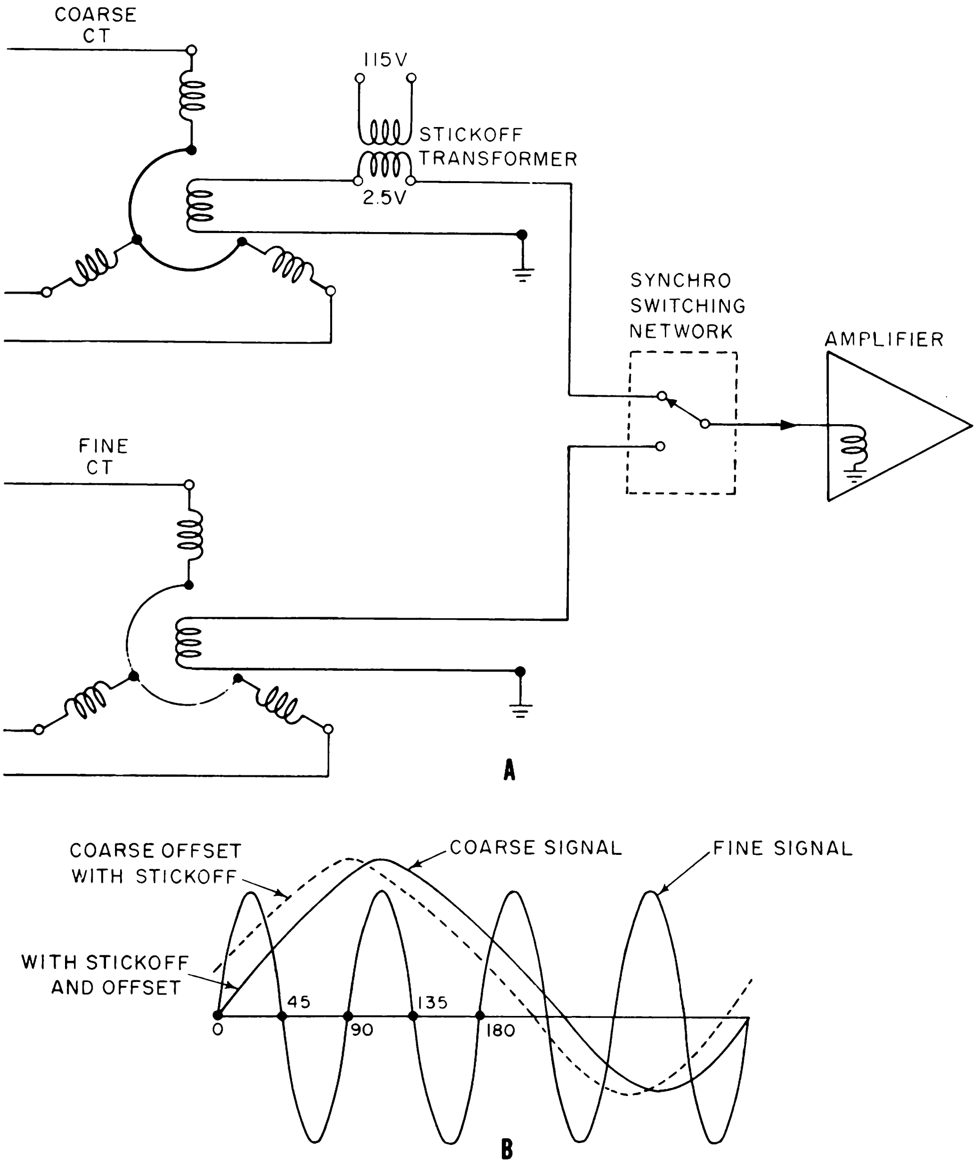
STICKOFF VOLTAGE

A servosystem will stop driving when the error signal is zero. A CT, however, has two positions 180° apart where its output is zero. Thus a servosystem controlled by a CT can synchronize at either position. This is possible in a dual-speed synchro system with an even speed ratio. Since both receivers are zeroed together both would be at the true correspondence and the false correspondence positions together. Hence a servosystem could not distinguish between the two positions. In fire control systems where remote and often unattended servosystems are used, the possibility that a false synchronization could occur must be eliminated.

As mentioned previously, no CT is perfect, and each has an inherent dead space. But the fine signal has little or no dead space to speak of. Therefore the slightest change in the signal or movement of the servosystem's response will bring the fine CT out of its dead space.

Once out of its dead space the fine CT will cause the servosystem to drive. You might think then that we do not have a false synchronization problem. But suppose that when the system is energized the transmitters and receivers are close to being 180° apart. The coarse signal would be too weak to assume control of the system, and the fine CT would have control. Therefore, the servosystem would drive until the fine signal is zero and remain there. The servosystem could not sense the difference between 180° and zero synchronization.

In order to make all positions distinguishable, a "stickoff" voltage (sometimes called anti-stickoff), is applied to the coarse signal. In figure 7-15A the secondary winding of the stickoff transformer is shown in series with the coarse CT output. The voltage induced in the secondary of the transformer in effect shifts the electrical zero position of the coarse CT. The



12.280

Figure 7-15.—Stickoff voltage in coarse signal circuit.

coarse CT is rezeroed and is offset from the fine CT by an amount equivalent to the stickoff voltage. This makes the coarse and fine CT put out zero volts at zero degrees but not at 180°, (fig. 7-15B). Now, the two positions are distinguishable to the servosystem.

TROUBLESHOOTING A SYNCHRO SYSTEM

Here we will discuss the symptoms produced by casualties in a synchro system. In a later chapter of this course, troubleshooting techniques such as the methods used to find a ground, short, or open in an electrical circuit are covered. Therefore, this discussion should be studied in conjunction with the general maintenance chapter.

Since a knowledge of operation is a basic requirement of maintenance, we will summarize synchro operation as related to troubleshooting. This will be a review of synchro action since the theory of synchro operation is covered in Basic Electricity.

Information is transmitted in a synchro system by voltage variations in the stator circuits. A synchro receiver compares its stator voltages with those of the transmitter's stator; the amplitude and phase of both sets of voltages are related to the zero reference position. A receiver reacts to a difference in voltage values by producing a torque, in a torque system, or passively, in a control system, by an induced voltage in its rotor. The receiver reproduces the conditions present in the transmitter to reconstruct the information. Hence a synchro system is a suppressed-carrier transmission system. The modulation of the signal voltages represents the information being transmitted.

Let's look at a torque system, (fig. 7-16). At correspondence the induced voltages in the two S1 coils are equal; the induced voltages in the two S2 coils are equal; and the induced voltages in the two S3 coils are equal. Since the stator voltages are bucking and equal, they cancel each other. The result is: no resultant voltages on the stator windings and NO CURRENT in the stators.

But remember that the transmitter rotor is turned and held in position mechanically, whereas the receiver rotor is free to turn. Now, if the two rotors are NOT displaced by the same amount, the voltages across S1-S1, S2-S2, and S3-S3 are NOT equal. And the unequal voltages set up currents in the stator windings. These currents create stator flux fields that exert TORQUE on the rotors. Result—the transmitter rotor remains stationary because it is held mechanically, but the receiver rotor is turned by the torque. The torque turns the receiver rotor until its position corresponds to that of the transmitter rotor. Thus the receiver follows every move of the transmitter.

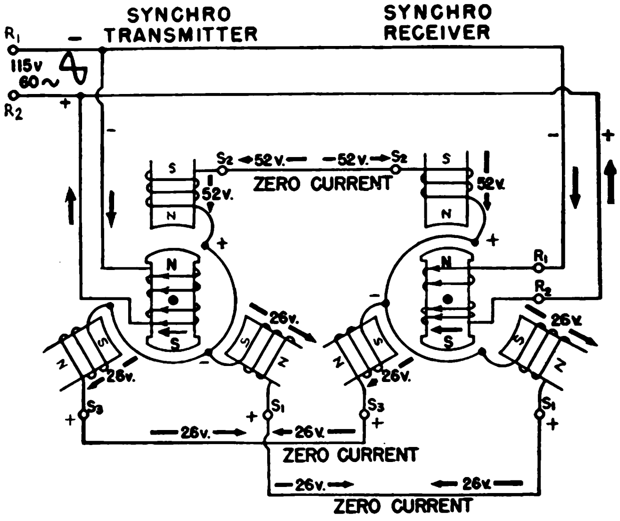


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Figure 7-16.—Torque synchro system.

Obviously the receiver's supply voltage must be identical to the transmitter's. Normally both are supplied from the same source. A synchro, by the way, is not a three-phase device, though you may get that impression from the 120° spacing of the stator windings. Synchro supply is from a single-phase, a-c power source.

In explaining synchro operation we discussed terminal voltages. Their most important practical purpose, however, is to find the electrical zero position of the rotor. Since the stator voltages are proportional to the position of the rotor, stator voltage readings are an aid in troubleshooting. There is a definite set of stator voltages for each position of the rotor. Therefore we can check a synchro's operation by comparing its voltage readings with its rotor position. For example, a voltmeter connected between S1 and S3 will read minimum voltage at the 0° and 180° positions of the rotor. Maximum voltage readings will occur at the 90° and 270° positions of the rotor.

Because synchros have a common electrical zero position, identical casualties will produce identical symptoms in all synchro systems.

Therefore we can relate an electrical casualty to the mechanical movement of the rotor, and by observing the behavior of a synchro's movements we can localize a casualty to a particular circuit. For example, in a properly zeroed torque system, a short circuit from S1 to S3 will cause the receiver to stop following the signal when it is at 0° or 180°.

We have assured that there is no mechanical trouble when we observe the receiver's motion. This of course is not a good assumption and should be checked. Remember that a synchro generates little torque. To be sure the synchro is not jammed mechanically, deenergize the system and turn the rotor by hand. It should rotate freely throughout its operating arc. The ease with which the rotor should rotate is a matter of judgment, but experience will soon teach you how to tell whether a synchro is free or jammed. It is a poor practice to use the dial to rotate a synchro. The dial is made of light material, and is easily bent.

After the mechanical check the torque produced by a synchro can be checked. At correspondence the torque is zero. With the system energized, a slight rotation of the motor should increase the torque. Vary the input to the receiver, so as to turn it through its complete operational arc, stopping at approximately 60° intervals. Observe how the receiver follows the signal, and at each stop check the torque.

OPENS, SHORTS, AND REVERSALS

The transmitted information is reconstructed in the receiver by the stator's resultant magnetic fields acting on the rotor's magnetic fields. The stator windings are physically located 120° apart. Therefore, it is logical to assume that each stator winding has an arc in which it exercises a predominate role in reconstructing the transmitted information. Hence casualties such as opens, shorts, or reversals can be correlated with the transmitted signal position and the reaction of the receiver. In OP 1303, First Revision, casualty symptoms are tabulated in this manner. Since this OP should be available to you, the tables will not be repeated here.

The maintenance techniques of finding a casualty in an electrical circuit are covered in the general maintenance chapter in this text.

SYNCHRO CONTROL SYSTEMS

In a synchro control system the rotor of the CT is not energized by the supply voltage. The CT stator windings are connected in parallel with the CX stator windings. Thus the currents present in the CT stator are proportional to the currents in the CX stator. The magnetic fields in the CT are a reproduction of the CX stator fields. The output of a CT is the voltage induced in its rotor. A comparison of the signal input with rotor voltage will check the operation of a CT.

PROTECTIVE DEVICES

Most synchro systems have one transmitter to transmit information to several receivers. These receivers are located at the various fire control stations throughout the ship. Because all the receivers of each system are in parallel, a fault such as an overload or short circuit in one instrument affects the operation of the entire system. When trouble occurs in such a system it is difficult to determine which unit is faulty. The use of overload and blown-fuse indicators provides a means of locating the faulty instrument. Various types of blown-fuse indicators are used. These devices usually employ small neon-glow indicators in parallel with the fuse element. Overloads are indicated by a trouble light that is operated by a small transformer located in the switch panels on the fire control switchboard.

REFERENCES

1. More detailed information concerning the theory, application, classification, and maintenance of all types of synchros is contained in OP 1303 (first Revision).

WARNING: The explanations of synchro action in this OP are based on the theory that electron flow is from positive to negative. Don't let it confuse you. Just reverse all polarities and hand rules and your answers will be in accordance with the present day theory of electron flow.

2. OP 1140, Basic Fire Control Mechanisms
3. NavPers 10086-A, Basic Electricity

FIRE CONTROL TRANSMISSION SYSTEMS

In our study of synchros we learned that a transmitted quantity is represented by electrical values in the signal circuit. Before we discuss other fire control transmission devices we will digress slightly to establish the concept of converting a quantity into a convenient form for transmission. Most fire control quantities have a numerical value. Numerals are symbols used to represent a quantity and will indicate the amount or position of the quantity along a scale or series of units. Hence a target range of 100 yards indicates that the target is so many, (100), units, (yards) away.

The unit of measure, yards, is not a convenient unit to use directly as a signal in a transmission system. A yard is a linear distance and would require a linear movement of that length to be used as a signal directly. If, however, we changed the unit to volts we could represent the target's range in an electrical circuit. We could now describe the range as 100 volts. This is not improper as long as the units (yard/volt) represent an equal distance and a change in range will result in an equal or proportional change in the number of units. Obviously the ratio of a volt per yard is too large and is not suitable for our purpose. We can change this ratio. We shift scale in many types of measure—miles to yards—degrees to minutes of arc, are examples. Thus we can make one volt equal to 10 or to 100 yards. As long as the ratio between the units of measure is constant throughout their operational range, we are not incorrect.

A quantity can be defined in many types of measures. Hence we can transmit quantities such as range, elevation, or traverse as voltages in an electrical circuit, as mechanical motions in a mechanical system, or as pressures in a hydraulic system. This is a basic concept in data transmission systems and in analog computers. We will discuss this concept further when we cover analog computers and telemetering.

Information can be transmitted by the presence or absence of a voltage. This is probably the simplest of data transmission systems. These systems, however, are limited in capability to the less complicated signals. Circuits similar to those in figure 7-17 are used to transmit an order or to indicate a condition. When the key or switch in the circuit is closed, the indicating device is energized.

The circuits as shown are simplified; frequently other switches or relay contacts are in series with the master switch. The other switches or contacts establish necessary conditions before the circuit is complete. For example, in order for the "On Target" flag to operate it is necessary for the computer to be energized, and possibly the computer and the director to be in the automatic or track mode of operation.

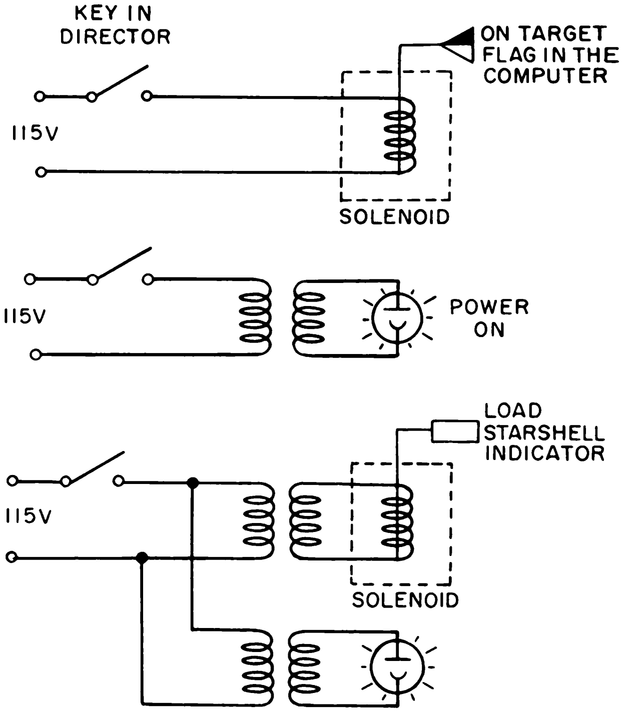

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Figure 7-17.—Simplified transmission circuits.

BALANCED BRIDGE CIRCUITS

Balanced bridge circuits are used to transmit information between remote instruments. Their principles of operation are identical to the bridge circuits used in electrical measuring devices (Wheatstone Bridge) covered in Basic Electricity. A balanced bridge circuit consists of two identical potentiometers connected in parallel with a common source of supply, (fig. 7-18). The wiper arms of the potentiometers are interconnected through a signal circuit which includes an input transformer in a servosystem. If the wiper arms are not at the same potential, current will flow through the signal circuit. The amount and direction of the current flow is determined by the potential difference of the wiper arms.

Assume that we wish to transmit range rate, which is measured in a radar receiver, to a computer. The device which measures range rate positions the wiper arm of the potentiometer in the radar receiver (fig. 7-18). The range rate

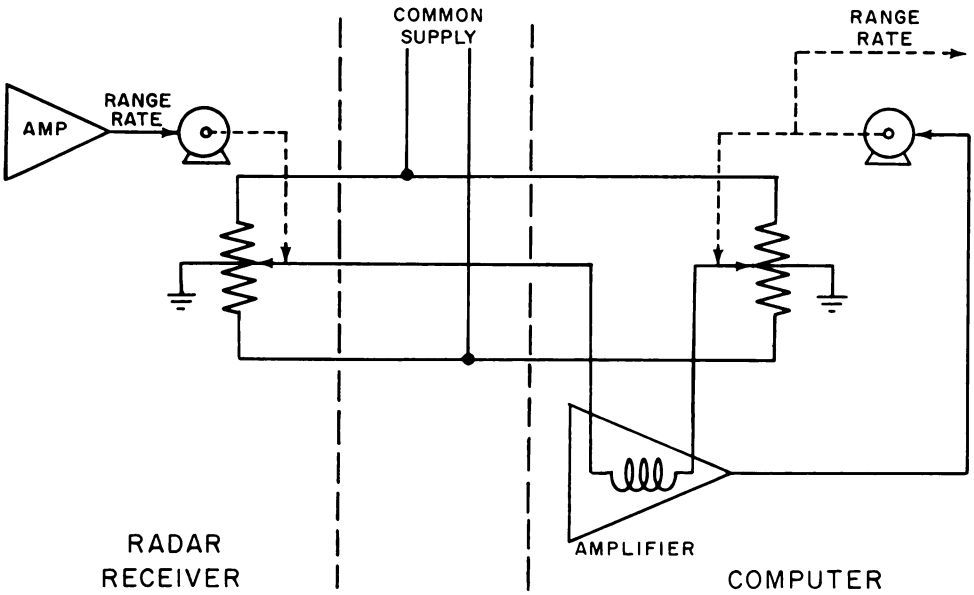

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Figure 7-18.—Balanced bridge circuit.

servosystem in the computer will drive the followup potentiometer's wiper arm until there is no current in the signal circuit. This condition will occur when both arms are at the same potential and hence at the same position on their potentiometers. Thus the followup wiper arm will follow any movement of the signal arm.

Since range rate can be either negative or positive, the potentiometers are grounded at their centers. The grounded positions of the potentiometers represent zero range rate. The grounds constitute a phantom connection between the centers of the potentiometers. When the wiper arms are in the section of the potentiometers below the grounds, range rate is negative, while above the grounds range ratio is positive. When the wiper arms are on the grounds the phantom connection shunts out the signal circuit.

THE MICROSYN

The microsyn, shown in figure 7-19, is frequently used as a torquer or pickoff in gyro units in director and antenna-positioning servos. Microsyns are also used in gyro units that are part of inertial guidance systems. The microsyn is an error-detecting, measuring, or similar device which can be used either as a transmitter (signal generator) or a receiver (sometimes referred to as a torquer, torque motor, or torque generator).

Either unit consists of a bobbin-shaped two-pole rotor and a four-pole stator. The four poles are displaced 90° from each other. A primary coil and a secondary coil are wound on each pole. The rotor has no windings, and serves only to change the reluctance of the magnetic paths between the stator poles. The rotor is mounted on ball bearings. Because it has no winding, no electrical connections such as brushes or sliprings are required.

When the microsyn is used as a transmitter, its output is a voltage whose phase is determined by the direction of rotor movement. The amplitude of the output voltage is proportional to the amount the rotor is displaced. When used as a receiver, its output is a torque—hence the name torquer or torque generator. The direction of the torque is determined by the phase relationship between the two input voltages, and its magnitude is determined by the amplitudes of the variable input voltage.

Microsyn Transmitter

In the transmitter or signal generator unit the four primary coils are connected in series and are excited by a 400-cycle reference voltage. Other frequencies are used, but 400 cycles is

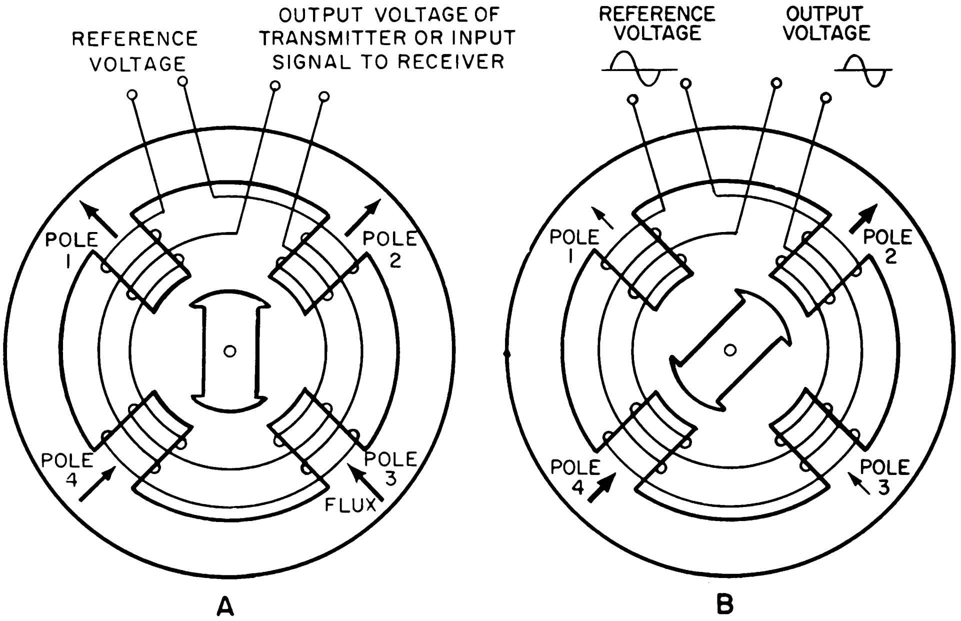

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Figure 7-19.—Microsyn torque or signal generator; A. Rotor at neutral position; B. Rotor displaced to the right.

most common. The coils are wound so that the flux in pole 1 aids the flux in pole 4, and the flux in pole 2 aids the flux in pole 3. When the rotor, which is attached, say, to the output shaft of a gyro, is in the zero position as shown in figure 7-19A, equal amounts of rotor iron are under each of the four pole faces. In this position, the pole 1-pole 4 flux through the rotor equals the pole 2-pole 3 flux through the rotor. Equal voltages are now induced in the secondary coils. These four secondary coils are also connected in series. The voltage induced in the pole 1 secondary aids the voltage induced in the pole 3 secondary. The combined voltages in the pole 1 and pole 3 secondaries oppose the combined voltages of the pole 2 and pole 4 secondaries. When the rotor is at the zero position, these two pairs of combined voltages are equal, and the output of the microsyn transmitter is zero.

When the rotor of the microsyn transmitter is turned to the right (fig. 7-19B) by a mechanical input, in this case gyro precession, the amount of rotor iron under poles 2 and 4 exceeds the amount of rotor iron under poles 1 and 3. The total voltage induced in the secondary coils of poles 2 and 4 now exceeds that induced in the secondary coils of pole 1 and pole 3. Under this condition the phase of the output voltage is that of the voltage induced in the secondary cells of poles 2 and 4, and the amplitude of the output voltage is equal to the voltage induced in secondary coils 2 and 4 minus the voltage induced in secondary coils 1 and 3. If the rotor of the microsyn is turned to the left, the magnitude of the output voltage equals the voltage induced in secondary coils 1 and 3 minus the voltage induced in secondary coils 2 and 4. Thus, the microsyn transmitter has an output voltage whose phase is determined by the direction of the rotor displacement from zero and whose amplitude is determined by the amount of this displacement.

Microsyn Receiver

This unit is physically and electrically identical to the transmitter. However, the rotor is free to turn. The rotor can be attached to the input shaft of a rate gyro. When the reference voltage alone is applied to the primary, the fields produced in the four primary coils will position the rotor to zero so that equal amounts of rotor iron are under each of the poles. If a voltage in phase with the reference voltage is applied to the secondary coils, the flux produced in poles 2 and 4 by these coils aids the flux produced by the primary coils. Meanwhile the flux produced in poles 1 and 3 by the secondary coils opposes the flux produced by the primary coils. The magnetic field produced in poles 2 and 4 is stronger than that produced in poles 1 and 3. Therefore a torque, exerted on the rotor, will attempt to increase the amount of rotor iron under poles 2 and 4.

If the phase of the voltage applied to the secondary coils is reversed, the direction of the resultant torque will be reversed. Therefore, it can be said that the microsyn receiver produces a torque whose direction is determined by the relative phase of the reference and signal voltages, and whose magnitude is determined by the amplitude of the signal voltage.

RESOLVERS

A resolver is a variable transformer capable of unlimited rotation. In its most common form it consists of a stator and rotor, each wound with two separate coils placed precisely at right angles to each other. This configuration is shown in figure 7-20. The two stator windings are normally stationary, and serve in some applications as the primaries. However, they may be used as secondary windings in other types of resolvers. The rotor windings serve also as secondaries or primary windings, depending on type and application of the resolver. The rotor assembly can be rotated with respect to the stator windings. Some resolvers have separate connections for each winding; others use one common lead for the primaries and another for the secondary. The common lead is usually connected to ground. Some types have extra windings for feedback, and others leave out either one primary winding or a secondary winding.

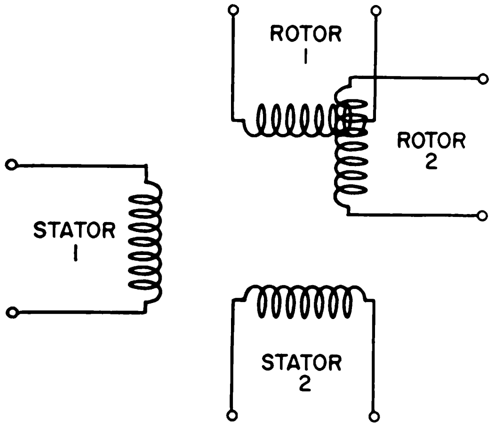

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Figure 7-20.—Typical resolver diagram.

Resolver Application

Resolvers are used extensively in computers, coordinate converters, in some radar sets, in weapon direction equipment, target designation equipment, and for data transmission. These devices perform electrical computations involving (1) resolution, (2) composition, and (3) combination. Here we are interested in resolvers used in data transmission systems. Computations performed by resolvers will be covered in a later chapter.

Resolver Operation

Briefly, if you apply an alternating voltage, labeled E in figure 7-21A, to the rotor winding (in this example the rotor has only one winding), the output voltages from the two stator windings will be sine and cosine functions respectively of the angular position (θ) of the rotor. In other words, as shown in figure 7-21 they will be equal to E sine (θ) and E cosine θ. Referring to the vector triangle in part B of figure 7-21, where the vector E is drawn as the resultant or hypotenuse of the triangle, you can see that the resolver actually breaks down or resolves vector E into its two rectangular components. This process is called resolution of vectors.

The voltages representing the two sides of the right triangle are applied to the stator windings of a second resolver, (fig. 7-22). This resolver is located in a remote instrument and is what we would call a receiver in the transmission system. The two input voltages, E sin θ and E cos θ, produce a resultant flux field. Voltages are induced in the two rotor windings,

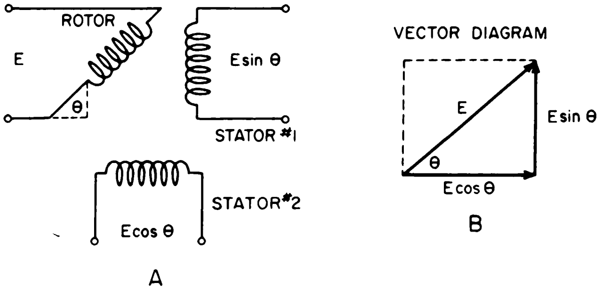

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Figure 7-21.—The resolution of a voltage.

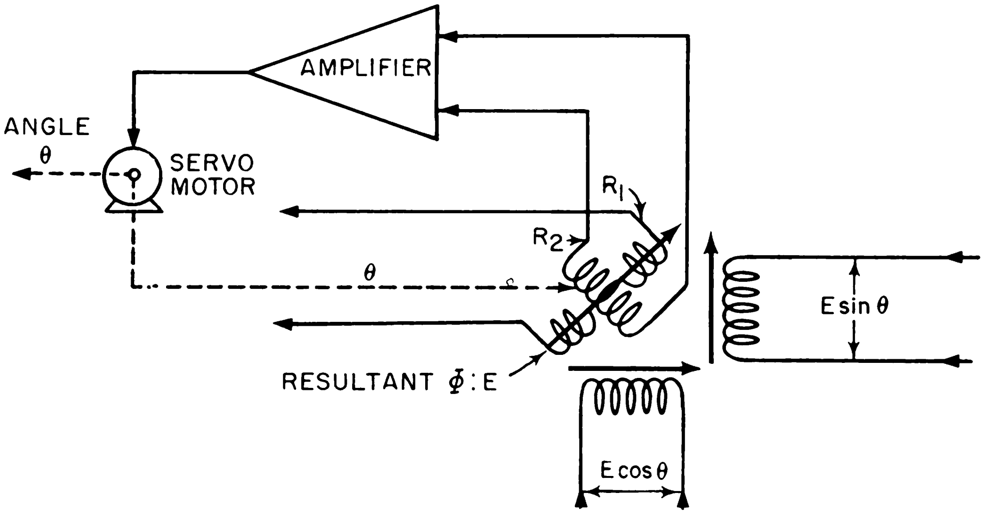

Figure 7-22.—Receiver in a resolver transmission system. 12.283

R1 and R2, from the field. R2 is connected to an amplifier in the servosystem. The servomotor will drive the rotor until R2 is at right angles to the flux field. At this position of the rotor its angle is equal to θ and no voltage is induced into R2. The winding R1 is cut by the entire flux field, and the voltage induced is proportional to voltage E (which represents the hypotenuse of the triangle.)

The resolver is at its null position with the rotor at angle θ and its output voltage proportional to the triangle's hypotenuse. If either of the stator input voltages changes, the resultant flux field will change and a voltage will be induced into R2 which will feed a signal to the amplifier. The servosystem will drive until the signal is again nulled. At this point the induced voltage in R1 represents the new hypotenuse and the rotor is again at the angle θ.

CHAPTER 8

SERVOMECHANISMS

Servomechanisms, called servos for short, are used extensively in fire control equipment. In the preceding chapter we referred to the numerous synchros in the Mk 1A computer. Most of these synchros are used in servos that control the position and movement of computing, indicating, and transmitting devices. The power drives in the director, radar antenna, gun mounts, and missile launchers are servos.

We will limit this discussion to an overview of the types of servos found in fire control equipment. First we will define a servo and summarize its operation. Then we will break a basic servo down into functional blocks. Next we will consider the operational requirements of servos for fire control equipment. In a later text in this series of training courses the theory of operation of servo components will be covered.

Servos are part of a broad class of control systems that operate on the principle of feedback. Figure 8-1 shows a block diagram of an elementary servo. The input signal to the servo is applied to an error detector and not directly to the amplifier. The input is an order signal, which indicates the desired action of the servo. The other signal to the error detector is a feedback signal which represents the output of the servo. The feedback signal is the reaction of the servo to the error signal, which is the input to the amplifier. The error signal is the difference between the input signal and the feedback signal. If there is a difference (error) between the input and output, corrective action automatically takes place to reduce the error toward zero.

The importance of the feedback principle can be seen from the elementary servo in the figure. The feedback signal forms a closed loop within the servo. In other words, there is a complete path through the servo to the load and back to the error detector. The output affects the input, and thus provides automatic followup control.

There is a type of servo called open loop which does not use feedback. In the open loop the output does not affect the servo's input. Automatic followup action is not possible in this type of servo. In this chapter we will cover only the closed-loop servo.

At this writing there is no standard definition of a servo. Therefore, for the purpose of this chapter, we will call a servo an electrical, electronic, mechanical, or hydraulic system which uses feedback. But a rigorous definition is relatively unimportant. What is important is that you know what makes a group of parts a servo. Regardless of their physical form—electric, electronic, mechanical, hydraulic, or combinations of these—all servos have the following characteristics.

SERVOMECHANISM CHARACTERISTICS

A SERVO IS A CONTROL DEVICE. The basic job of the servo in figure 8-1 is to position a load. The load may be a director, a radar antenna, a computing device, or a hydraulic valve. The load is attached in some manner to the output of the servo. Consider a director. Its position is controlled in accordance with train and elevation orders which are inputs to the servo.

A SERVO IS A POWER AMPLIFIER. The input to a servo is usually a very small signal. It is too weak to move the load by itself, so some sort of power amplification must take place within the servo. Again take as an example a servo used to position a director. The input to the servo is sometimes so small it can be measured with a milliammeter. To develop enough power to move the great weight of a director requires currents in the amperage range. Therefore, most servos you will work

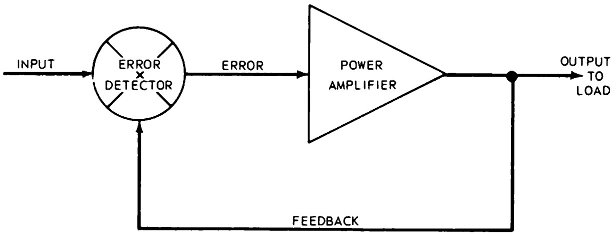

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Figure 8-1.—Block diagram of an elementary servo.

with have one or more amplifying stages. The amplifier may be electrical, electronic, hydraulic, or two or more of these in combination.

A SERVO IS A CLOSED-LOOP SYSTEM. Look again at figure 8-1. You can see that the feedback line runs from the output to the block marked error detector. This feedback is a communication channel which reports the speed or position of the output back to the error detector. To see how feedback works, assume that the input is a mechanical signal telling the output to move to a certain position. The feedback signal reports the position of the output to the error detector. The error detector performs a simple mathematical operation: it subtracts the output from the input to get the amount of difference, or error. And the error, rather than the quantity marked input, is the actual input to the amplifier.

Note that when the feedback equals the input, the error signal is zero. But whenever the feedback differs from the input, an error signal is developed. The error signal drives the output in such a manner as to reduce the error signal.

Keep in mind that feedback can be transmitted electrically, hydraulically, or mechanically in a servo. Feedback is also called response.

A SERVO IS AN ENTIRE SYSTEM. It cannot consist of a single component. It must have the minimum number of components we have shown in the block diagram in figure 8-1. There is no law against a servo having more sections than the ones we have shown. And they usually do. But regardless of the number of parts in a servo, they all work together as a system or team. And this system concept is important. A servo is not an isolated motor or power amplifier, but must be considered as an entire system of interconnected components. Together, these components measure, transmit, compare, amplify, and control quantities.

FUNCTIONAL SECTIONS OF A SERVO

So far, we have talked about the essential elements in servos—the "bare bones" so to speak. We reduced a servo to its minimum number of functional blocks. Now we will expand our servo horizon by increasing the number of working blocks from two to three, and then discuss each in turn.

Figure 8-2 is a three-block diagram of the elementary servo shown in figure 8-1. Each block has a label that describes its function.

Our new block diagram differs from the first one in that the power amplifier has been divided into two parts: an AMPLIFIER and an ERROR REDUCER. The amplifier increases the weak error signal, and it controls the error reducer. We have coined the term error reducer because the name closely describes the function of this servo section, which is to drive the output of the servo until it is equal to the input, thus reducing the error nearly to zero. Keep in mind that there can never be zero error. The error reducer must receive an error signal before it can control the output. However, the error signal should be kept as small as possible.

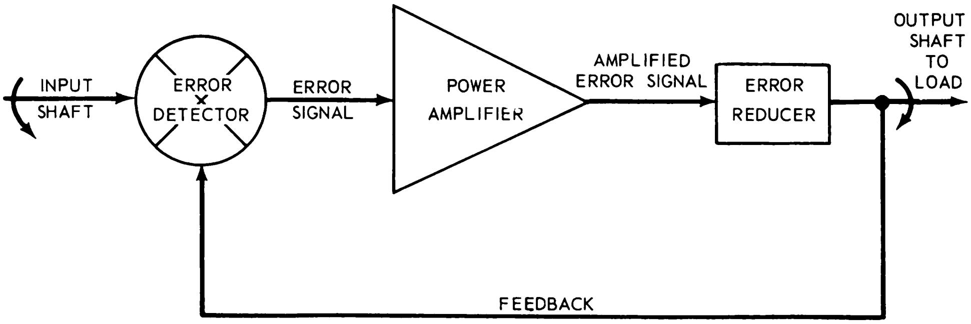

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Figure 8-2.—Block diagram of an elementary servo.

In the servo in figure 8-2 the input, output, and feedback devices are mechanical shafting; the error detector is an electromechanical device; the amplifier is electronic; and the error reducer is an electromechanical unit.

Earlier, we described a servo as any device that uses the principle of feedback. It can also be defined as a mechanism whose output tries to reproduce its input. Let's look at how the servo blocked out in figure 8-2 works, based on this point of view. Assume that the input and the output shafts are at the same position. There is no error between them, and so there will be no error signal to the amplifier. Therefore, the error reducer will not receive a correcting signal and the servo will not move. But if the input shaft is suddenly turned to a new position, there will be an instantaneous anuglar difference between the positions of the input and output shafts. Where is this difference detected and measured? The answer is, of course: at the error detector. The input and feedback shafts are both inputs to the error detecting device, which, as we said before, is electromechanical. Since the feedback shaft is geared to the output shaft, the feedback duplicates any position and motion of the output. In other words, knowledge of what the output shaft is doing is fed back over the feedback line to the error detector. Here, the positions of the input shaft and output shaft are compared. The error detector measures any difference between them, and then it does something more. It changes mechanical position error into an electrical error signal. The electrical error output of the error detector is directly proportional to the angular difference between the input and output shafts.

The electrical error signal is relatively weak. So, it must be amplified. After it is amplified, it is sent to the error reducer. Here, the error signal is changed from its electrical form to a proportional mechanical signal. Now the error reducer drives the output shaft in a direction which reduces the error between the output and input shafts. As the output shaft turns, so does the feedback line. But it turns in a direction that reduces the difference between the input and feedback signals. When the output and input shafts are in agreement, the output of the error detector is zero. The amplifier "sees" no signal at its input, and the servo stops.

Now if we turn the input shaft at a constant velocity, the output shaft should turn to the same position as the input shaft, and follow it at the same speed and in the same direction. If the input shaft were to speed up, then reverse its direction, the output shaft should faithfully reproduce these mechanical gymnastics; and all the while the two shafts should remain closely aligned. If at any time they do not, then the error detector will produce an error signal. This signal is amplified and sent to the error reducer. It then drives the output shaft until the error between the input and output is as nearly zero as possible. When this condition exists, the servo is said to be "nulled." Other terms that describe zero or nearly zero error are: synchronized, in synchronism, and in correspondence.

In the preceding pages of this chapter we have given you a general idea of the functional sections of a servo and what they do. You learned that the input is the controlling quantity. We described it as the displacement of a shaft. In practical servos or power drives the input is generally an electrical quantity which represents a shaft position. The servo error is the difference between the input and output of the servo. The error detector is the device which compares the input with the servo output. The error reducer is essentially the prime mover of the servo. It is controlled by the amplifier section, which simply increases the strength of the error signal so that it can move the error reducer. We mentioned the load earlier. While the load, strictly speaking, is not a component of the servo, load characteristics (size, weight, etc.) have an important bearing on the design and operation of the servo.

SIGNAL TYPES

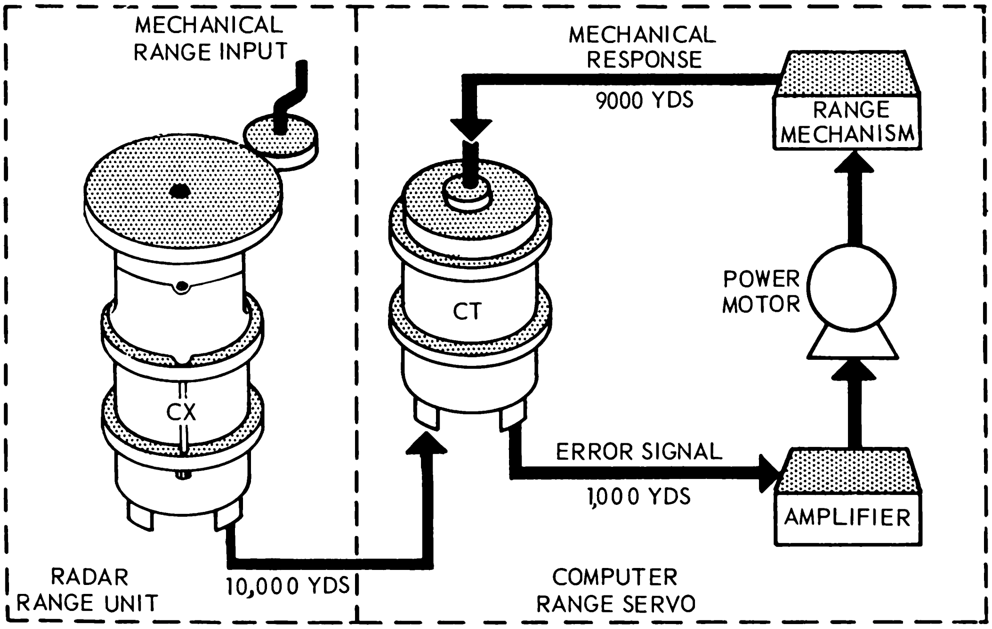
A servo's output is an accurate duplication, with an increase in power, of the input order signal. The order signal represents the desired action and therefore determines the servo's response. The order can be a position a velocity, or an acceleration signal. Let's consider the three types of order signals. Position is a relative quantity which indicates a place or point in a scale of measure or reference frame. Hence position is a scalar quantity and it has no further meaning. Movement from a position results in a displacement. Displacement is a vector quantity having both magnitude and direction. If we time a displacement we can obtain a velocity. Velocity is a timed displacement; that is, the rate of change of position. Velocity then is a vector quantity being derived from displacement, also a vector quantity. (Incidently, speed is a scalar quantity having only magnitude.) A change in velocity is an acceleration. Hence acceleration is a vector quantity. Strictly speaking, an acceleration is a change in velocity and therefore can be either an increase or decrease in speed or a change in the direction of motion

Scalar quantities can be combined by simple arithmetic. Vector quantities, however, are more difficult to combine. Since both direction and magnitude are involved, vector addition is required. It is the job of the error detector in a servo to combine the input and feedback signals whether they are vector or scalar quantities. Vector quantities can be combined by simple arithmetic if their directions are along a common axis. In servos the output is a duplication of the input and therefore their directions must be common.

Order signals often must be converted from one type to another. For example, the fire control radar will measure the displacement of a target from the line of sight. From this displacement a velocity is derived to change the rate of motion of the director. On the other hand we may have a computed rate of motion and require the displacement which will occur during a given time. We can change the signal because displacement, velocity, and acceleration are functions of each other and each is a derivative of the other. A derivative is a quantity which is obtained from another. If we know that a displacement occurred in a measured interval of time we can derive the rate of motion. And it follows that if we know the rate of motion we can derive the displacement which will occur during an interval of time. The derivatives are obtained in servos by integration. We will not go into integration here since it can be reasoned that if one of the quantities and time is known, the other quantities can be derived.

POSITION SERVOS

We will use the range receiver in the computer as an example of a position servo. Assume that the target is stationary. (This will give us a fixed position signal, and simplify our explanation. Later on we will introduce movement of a position signal.) Assume that the fire control radar has measured target range at 10,000 yards. The CX in the radar, (fig. 8-3), will transmit range to the CT in the computer. Assume that the range servo in the computer is at 9,000 yards. Hence the CT, the error detector, will not be at its null position. The error signal from the CT will be proportional to the 1,000 yards displacement between the ordered position and the actual position of range in the computer. The servo will drive until response positions



12.286

Figure 8-3.—Position servo.

the rotor of the CT at its null position, which represents 10,000 yards range.

The error detector compared two positions to obtain an error signal equal to displacement. As pointed out in the previous chapter, synchros are basically position-sensing devices. Resolvers and balanced bridge circuits can also detect displacement, and are sometimes used in position servos. In the next chapter we will discuss gyroscopes and their use in servos. Gyroscopes are fundamentally position-sensing devices, since they can measure displacements.

In a position servo the error signal is kept at a null by reducing the displacement between the input and output signals of the servo. The speed of a servo's response is a function of the magnitude of the error signal. For all practical purposes the error reducer's output torque is proportional to the control voltage from the amplifier. The gain of the amplifier is constant. We will disregard the stability feedbacks to the amplifier, which we will take up later. The output of the amplifier, which is the input to the error reducer, is equal to the product of the amplifier's gain factor and the magnitude of the error signal. Thus for large displacements the servo will drive rapidly toward correspondence. The error signal is reduced by servo response; this is inherent in servos. Therefore, near correspondence the servo's speed is reduced.

After the servo is in correspondence, a slight movement of the order signal will cause a displacement in the error detector, with a resulting error signal to the amplifier. Hence the servo will follow changes in the input signal as a function of displacement.

A position servo will faithfully follow changes in position; but in a dynamic system there will always be an error. In a system where the input signal is constantly changing position, the servo will tend to average out the velocity of the input signal and follow at this rate. Since a displacement is necessary to obtain an error signal, the servo's output will lag the input. To overcome this limitation in dynamic systems such as the target tracking loops, the input signal to the servo is proportional to velocity. Since a servo's output is a reproduction of its input, the output is proportional to a velocity and not a position. Hence the servo's load will move at a rate determined by the input signal.

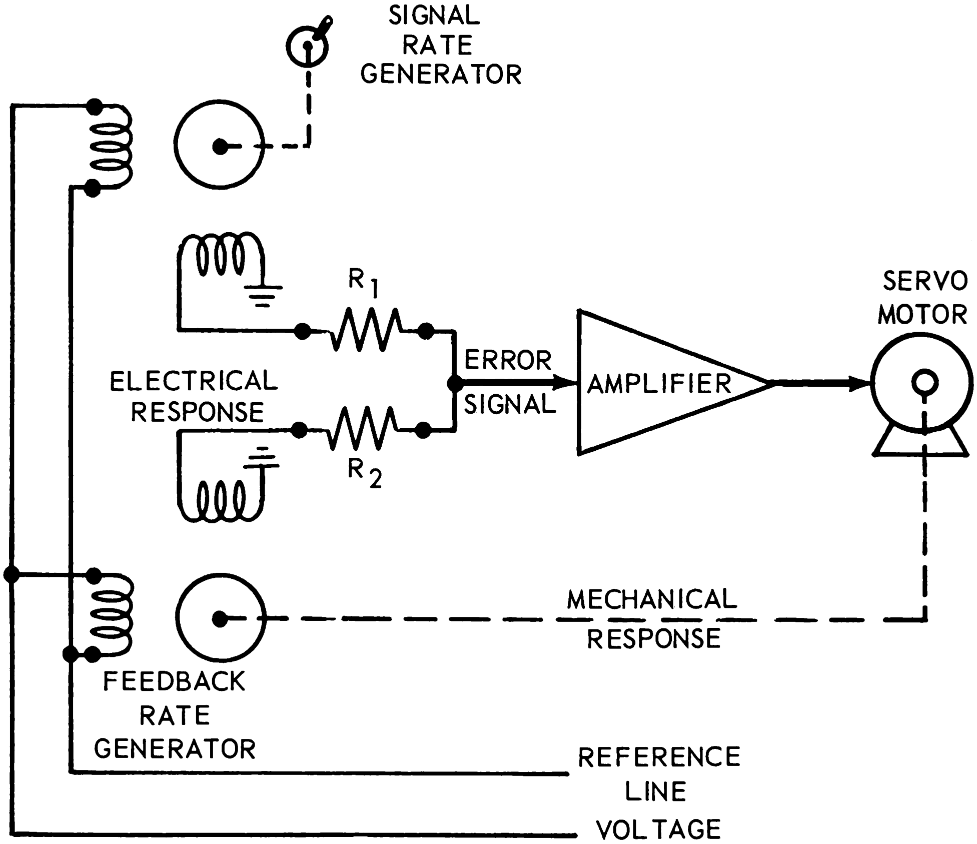
VELOCITY SERVOS

In velocity servos the input signal is proportional to a rate. The velocity of the output is the primary function of this type of control. Position is a second order function, being derived from the velocity of time. (In position servos velocity is a second order function which is derived from position, the primary function, and time.) Hence a velocity servo's primary function is the opposite of that of a position servo. The basic functional elements of the two types are identical; each has at the very least an error detector, an amplifier, and an error reducer. In position servos the error signal represents a displacement, and is eliminated by reducing the displacement. In velocity servos the error signal voltage is proportional to a velocity, and is eliminated by a response voltage proportional to the output velocity.

A block diagram of a velocity servo is shown in figure 8-4. The rate generators in the diagram develop a voltage proportional to the velocity of their rotors. The generators are identical. Their windings are displaced 90° from each other. The reference winding is energized by the line voltage and sets up a magnetic field in the generator. Since the windings are 90° apart, the generator's output is zero when its rotor is stationary. If the rotor is turned, it will distort the magnetic field and cause a voltage to be induced in the output winding. The amplitude of the output voltage is proportional to the magnetic field's distortion and hence to the velocity of the rotor. The phase of the output voltage is determined by the direction of the rotor's movement.

The output voltage from the signal rate generator is the input to the amplifier via resistor R_1 (fig. 8-4). The magnitude of the signal is proportional to the velocity of the rotor, which we will turn with the handcrank. The phase of the signal is determined by the direction in which the rotor is turned. The signal is amplified, and drives the servomotor. The motor drives the load and the response rate generator. The output of this generator is fed back to the input circuit of the amplifier via R_2. The response voltage is 180° out of phase from the input signal voltage. The servo's error detector is the summing network consisting of the resistors R_1 and R_2. When the magnitude of the response voltage is equal to the input signal voltage, the two will be in balance and the error voltage will be zero. This will occur when the servo's output velocity is equal to the desired velocity.

Note that the position of the output is not considered in the explanation. Position is a function of velocity and time in this type of



12.287

Figure 8-4.—Velocity servo.

servo. Acceleration is a change in velocity. Hence if we changed the speed of direction of rotation of the handcrank in the diagram, the change in the generator's output would be proportional to an acceleration signal.

SERVOMECHANISMS IN FIRE CONTROL

Servos have countless applications in fire control. Directors, radar antennas, computing devices, gun mounts, and missile launchers are positioned by servos. The operation of modern fire control equipment is almost fully automatic, and largely dependent on data from remote sources. To obtain smooth, continuous, and accurate operation, the information flow is normally best controlled by itself. But the power produced by transmission devices such as synchros is not large enough to do appreciable amounts of work. As you know, servos are closed loops capable of controlling and amplifying information signals. In this area alone the use of servos has increased tremendously in the newer equipments. This can be illustrated by a comparison between an early gun computer and a missile computer. The gun computer has approximately 20 servos; the missile computer has about 40 servos.

OPERATIONAL CHARACTERISTICS

The operational characteristics of a servo are determined primarily by its job. There are just about as many different types of servos as there are jobs for servos to do. Generally speaking, a servo has a common purpose—to control its output in a manner dictated by its input. Ideally, the motion and position of the output shaft should duplicate the motion and position of the input shaft. But we never get ideal performance from servos. We will discuss the major reasons for this, and show some of the approaches taken to improve servo performance.

There is always a time lag between a change in the input signal and the servo's reaction to the change. Any physical motion requires time. In addition, the error signal must have sufficient magnitude to cause the servo to drive. Below this level the servo is insensitive to signal change. The servo's time lag will be decreased, and its sensitivity to small signal changes increased, by an increase in the gain of the amplifier. But if the gain is set too high the servo output will tend to oscillate, and to be unstable. Hence the gain of a servo is limited by stability considerations. The sensitivity of a servo is counterbalanced against its stability to obtain the best operation.

Input signals to a servo always contain some roughness, such as noise in an electrical signal. This roughness must be eliminated to obtain smooth operation. Let's consider a director train power drive with a position signal from a CX-CT synchrosystem. There are physical limits to the rapidity of the director's movements. Slow variations in position must be accepted as possible director motion, but rapid fluctuations in the signal may be rejected as being impossible for the director to achieve. Thus by an examination of the signal's frequency spectrum we can detect and eliminate known noise frequencies. Filters in the signal circuit can shunt noise frequencies away from the amplifier, and allow only those frequencies that represent director motion to enter the amplifier.

If the capabilities of a servo's load are known, we can attenuate or eliminate some of the unwanted frequencies in the signal. In other words, a bandwidth for the servoamplifier is established. The bandwidth must include all the frequencies that could represent valid signals. Hence frequencies which are actually caused by noise but could represent valid motions of the signal must be accepted. Damping and stability feedbacks are used to reduce this roughness in the servo. We will cover damping separately, later in the chapter.

An increase in bandwidth causes a corresponding increase in noise generated in the amplifier, and a loss in gain. The response signal fed back to the error detector is proportional to the amplifier's output and contains any noise generated there. Since response is 180° out of phase with the input signal, it is a negative feedback. Consequently the advantages of negative feedback are applicable to servos. One of these advantages is that nonlinear distortions and noises generated in the amplifier are reduced by response.

Response in a servo tends to make the overall gain of the amplifier independent of variations in load, supply voltages, and aging of the tubes. This gives the amplifier a constant gain factor and the servo a flat amplitude response curve. A constant gain factor will provide a linear relationship between the input and output signals of the amplifier throughout its operating limits. Therefore an error signal of a given amplitude will produce an output signal with a definite amplitude. The amplifier's output is, of course, the control signal to the error reducer. Hence if the error reducer has a linear relationship between control voltage and torque produced, the servo's response will be directly proportional to the error signal.

Variations in the gain of a servo are sometimes desirable to compensate for load variations. Consider the director train servo we spoke of before. The director has mass, and therefore has inertia. Inertia is the property of a body which resists changes in motion. A change in motion is an acceleration, and a force is required to accomplish acceleration. Since the director has inertia, a larger force is necessary to start the director into motion or to accelerate the director's motion than the force required to maintain the director at a constant velocity.

Assume the director is tracking a target which causes the director to train at a constant velocity to the right. Now assume that the target changes course, requiring the director to reverse its direction and train to the left. To do this the train servo must first stop the director's movement to the right. Since the director has inertia, there is a sudden increase in the load on the servo as it attempts to stop the director. The error signal to the servoamplifier does not reflect this increase in the load due to inertia. Hence there is a time lag before the director is stopped and started to the left. The time lag can be reduced if the gain of the amplifier is varied to compensate for load variations.

The load's variation is due to acceleration. Thus a signal proportional to a change in the load's velocity could be used to vary the amplifier's gain. The velocity feedback signal would originate at the load from a source such as a rate generator.

The amplifier's gain is sometimes varied by the amplitude of the error signal. When there is a large displacement between the load position and the ordered position we would want the servo to accelerate rapidly to its maximum velocity and to maintain that velocity until the load is close to the ordered position. The error signal to the amplifier could be used to shift circuits in the amplifier to vary its gain. When the error signal's amplitude reached a preset level it would automatically shift the gain.

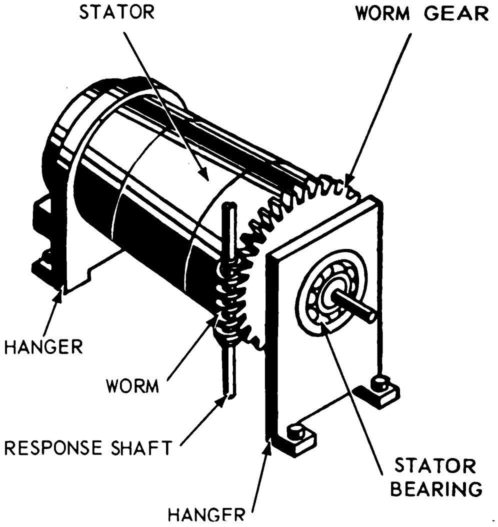
TYPES OF POWER SYSTEMS

The input signal to a servo is weak, and a large boost in power is needed before the servo can do its job. The type of power used in a servo is determined by its job. Electric servosystems are used with light loads. But if the load is large and variable, the servo must have an amplifier to increase the signal power supplied the error reducer. Most servos in fire control equipment are electromechanical; the amplifier is electronic, and an electric motor is used as an error reducer. There are, however, a few electrohydraulic servos in fire control. In the hydraulic servos the input signal is amplified in an electronic amplifier. The amplified signal controls an electric device which in turn controls the hydraulic power system.

Each type of power has advantages. The electric servo is the simplest. An electronic amplifier is flexible, and can adapt the servo to the load. Thus the electronic system provides positive control at variable speeds. Hydraulic systems cannot be backed down by the load. Thus they are used with heavy loads subject to sudden and drastic changes. Radar antennas which have a large area exposed to the effects of the wind force and to gun blast are examples of this type of load.

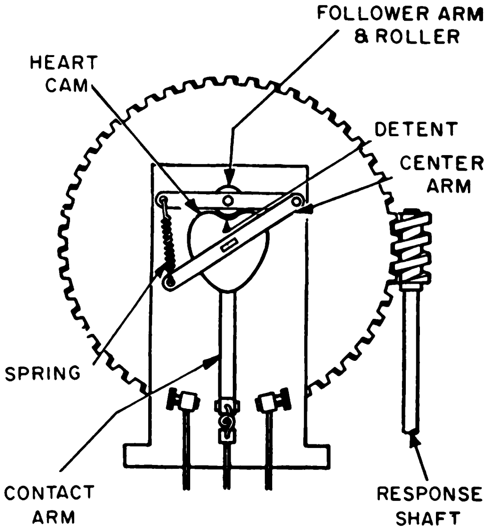
Electric Servo

In an electric servo, a bearing-mounted synchro (fig. 8-5) operates a set of contacts which control the supply voltage to a servomotor. The motor will drive whenever the synchro closes the contacts. Response from the motor will drive the synchro in the opposite direction from the synchro's signal, and open the contacts. Thus the servo operates until the synchro signal is reduced to zero.



12.171
Figure 8-5.—Bearing-mounted synchro receiver.

Look at figure 8-6, which shows one end of a synchro receiver, to see how the bearing-mounted synchro controls the servo contacts. The response shaft of the synchro'is driven by the servomotor, and it rotates the synchro stator. Now find the HEART CAM and CONTACT ARM on figure 8-6. The contact arm is secured to the heart cam. But both the arm and cam are ball bearing-mounted on the synchro rotor shaft. Neither the arm, the contact, nor the cam turns DIRECTLY with the rotor shaft. But the CENTER ARM is secured to the rotor shaft. This center arm drives the FOLLOWER ARM and ROLLER. The SPRING keeps the roller in the DETENT of the heart cam.



12.173
Figure 8-6.—Heart cam and contact assembly.

Now imagine an electric signal turning the rotor. As the rotor turns, the center arm, follower arm, and roller drive the heart cam. And as the heart cam rotates, it closes the contacts at the contact arm. This closes the circuit to the servo, and the servo starts driving.

As the servo drives its load, it also drives the response shaft, and the response shaft turns both the synchro stator and rotor. As the stator and rotor turn in response, the heart cam drive tends to open the contacts. But these contacts are not opened until the response equals the original signal—until the rotor is turned as much by RESPONSE as it was turned by the electrical signal. This means the contacts open and stop the servo as soon as the servo has driven out the signal. Result—the servo drives out the signal given by the bearing-mounted synchro.

Briefly, the ELECTRICAL SIGNAL to the rotor STARTS THE SERVO. And the mechanical RESPONSE to the stator STOPS THE SERVO.

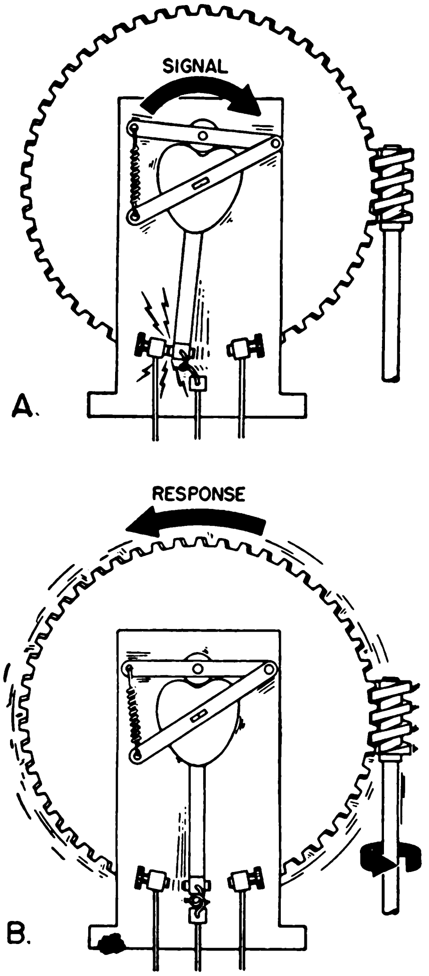
Figure 8-7 reviews this signal-response action. Figure 8-7A shows the signal turning the synchro rotor and closing the servo contacts. This starts the servo driving.

Figure 8-7B shows the response driving both stator and rotor of the synchro receiver. When the response equals the signal, the contacts are centered, and the servo stops.

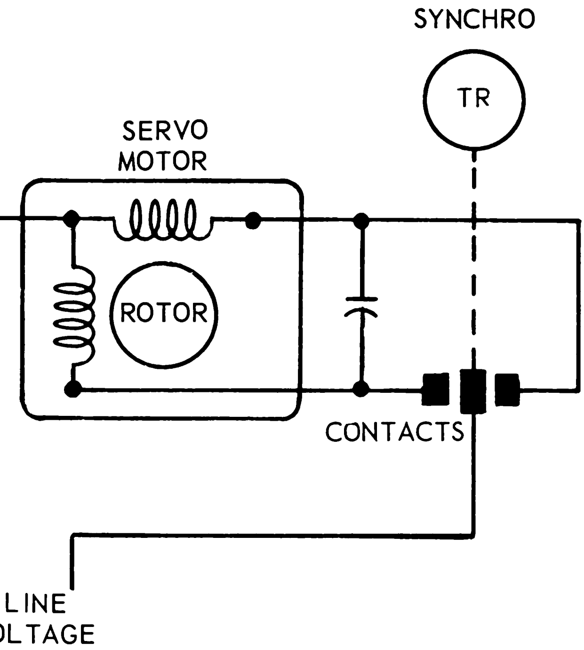
You're probably wondering why the contact arm here is driven by the heart cam assembly. Here's the reason: A large electrical signal turns the synchro rotor with considerable torque. The torque closes the contacts at the contact arm. Then as soon as the contacts are closed, the spring stretches and the roller gently rolls out of the detent. This frees the rotor so that it can follow the signal, without exerting any more force on the contacts.

Without the heart cam drive, the rotor would continue to drive against the closed contacts. And this might damage the contacts or throw the rotor shaft out of line. Thus, the heart cam drive prevents damage for large electrical signals.

Figure 8-8 shows the electrical arrangement of the servo. The servomotor is a 115 VAC motor with split phase operation. The capacitor in the circuit shifts the phase of the voltage to one of the motor's windings. The contacts determine which winding will receive the shifted voltage and hence which way the motor will drive. One side of the line voltage is connected to the common point between the stator windings of the motor. The other side of the supply is connected to the center contact which is connected to the rotor of the synchro. A signal to the synchro will cause the center contact to rotate and to complete the circuit to either the left- or right-hand outer contact. Note that either of the outer contacts will complete the circuit to the motor, but by separate paths. The capacitor will be in series with one of the motor's windings. Which winding is determined by the contacts, hence by the synchro signal. The capacitor will shift the phase relationship of the voltages applied to the windings. The motor will drive until response opens the contacts.



12.174
Figure 8-7.—Signal-response action.



12.288
Figure 8-8.—Electrical servo.

The advantages of electric servos is their nplicity. Their disadvantages are the lack of eed control and their limited current-carrying pacity. The servo is either synchronized or iving, and thus is strictly a position control. e low torque of the synchro limits the size of contacts and hence their current-carrying pacity. This, in turn, limits this type of servo light loads.

ectromechanical Servos

Figures 8-3 and 8-4 show block diagrams of presentative electromechanical servos. The nal input to the amplifier is either an a-c or -c voltage representing a desired position or ocity of the load. Obviously the primary ction of the amplifier is to increase the ength of the error signal. But an amplifier many features which can be used to improve servo's operation. Many types of amplifiers used in servos. Therefore, it is not prac- al to discuss individual amplifiers in this t. We will discuss some of the advantages of ing an amplifier in a servo.

An amplifier can increase the signal power practical level. The amplifier may be made sitive to signals with a certain frequency, amplitude, type of voltage, and phase or polarity. The amplifier isolates the signal source from the load. The error signal feeds into the fairly constant impedance of the amplifier's input circuit, and not into the variable impedance of the load. At the same time, however, the amplifier's gain can be varied by feedback signals to automatically adjust the amplifier's output to compensate for the condition of the load.

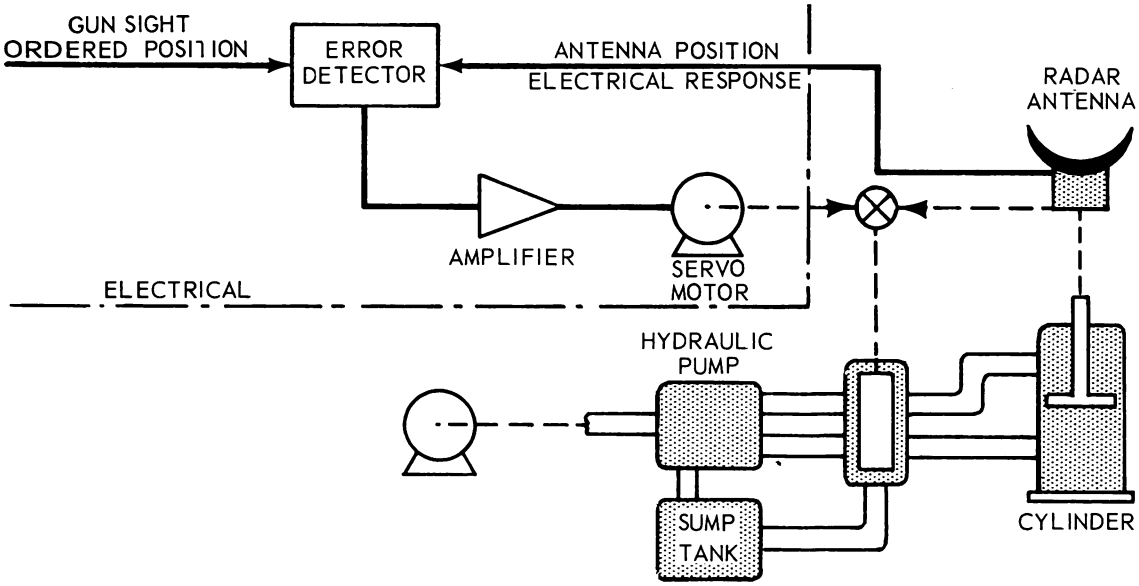
The theory of operation of electromechanical servos is identical to that of all closed-loop servos. Response from the output is fed back to the input to null the error signal. The amplifier has a large power source which is controlled by the low-powered error signal. The amplifier can detect the direction in which the load must be moved by the phase or polarity of the error signal. The amplitude of the error signal determines the amount or the velocity of the servo's output.

Electrohydraulic Servo

Figure 8-9 shows a simplified block diagram of the radar antenna position system in the GFCS Mk 63. The electrical section of the drive is a typical electromechanical servo. The output of this section, however, does not move the antenna directly, but is used to control the hydraulic section of the drive. The servo motor controls the movement of the servo valve through a mechanical differential linkage.

The servo valve governs the flow of the high-pressure hydraulic oil to the antenna positioning cylinder. In its neutral position the servovalve blocks the flow of hydraulic oil to the cylinder. The high-pressure oil trapped in the upper and lower chambers of the cylinder forms a hydraulic lock on the piston. The piston, hence the antenna, are frozen in their positions by the lock.

When the servomotor moves the servovalve from its neutral position, one of the cylinder chambers will be connected to the high-pressure line. The direction in which the servovalve is moved by the motor determines which chamber is connected to the high-pressure line. Movement of the valve connects the opposite chamber to the sump tank to allow the oil in the chamber to drain off. The high-pressure oil forces the piston in the cylinder to move. The speed at which the piston will move is determined by the rate of delivery of the oil to the chamber. This is determined by the amount the servovalve is moved from its neutral position. The total movement of the piston (antenna), is determined



12.289

Figure 8-9.—Simplified block diagram of an electrohydraulic servo.

by the volume of oil to the chamber. This in turn is determined by how far the servovalve is moved from its neutral position, and how long it remains off its neutral position.

Response from the antenna is used to bring both the electrical and the hydraulic systems to their null positions. This makes sense since both systems must stop driving when the antenna is at the desired position. If the response voltage from the antenna is equal and opposite to the input signal voltage, the electrical signal error is zero. The output of the amplifier to the servomotor is zero, and there will be no torque on the motor. The hydraulic system is at null when the servovalve is in its neutral position. Mechanical response feeds through the differential linkage to zero the servovalve as the antenna moves. Thus the input to the servovalve is proportional to the difference between the movement of the servomotor and the movement of the antenna.

Conversion Between Systems

In the explanation of servo operation we shifted between electrical (voltage), mechanical (motion), and hydraulic (pressure) energy. Let's consider what is involved in the conversion between types of energy. The servo's input signal represents a desired motion of the load. Hence, a relationship must exist between the signal and the movement of the load. The ratio of signal strength to load movement is maintained throughout the servo. Thus if the signal is converted to a different type of energy, the relationship between the energy systems must be proportional to that of the signal to load movement. This factor also applies to the amplification of the signal's power within the servo. The ratio between the power levels is a function of the ratio of signal to load movement.

In the chapter on synchros you learned that a relationship exists between the stator voltages of a TR and its mechanical output. A TR, therefore, can be used in servos to convert an electrical signal to a mechanical signal. This is shown in figure 8-8. The power motor in the figure is also a converter of energy types, that is, a transducer, since it has an electrical input and a mechanical output. Response which is proportional to the movement of the load is fed back from the motor to the TR to cancel the input signal. Obviously, then, the relationship between the input signal and the load movement is maintained throughout the servo even though the type of energy was changed several times.

Basically, to change to another form of energy in a servo, an electrical signal must produce a proportional mechanical motion. It follows that a signal represented by a mechanical motion must produce a proportional electrical voltage. The same relationship exists in the electrohydraulic servo shown in figure 8-9. The servomotor produces a torque (mechanical force), which is proportional to the voltage (electrical pressure), supplied by the amplifier. The output of the motor moves the servovalve which controls the hydraulic flow.

Most servos have a linear relationship between signal strength and load movement. In some computing servos, however, this relationship is not linear. The servo output is made to vary in accordance with an independent quantity introduced into the servo. We will cover this type servo in chapter 11 of this text.

An electronic amplifier in a servo provides a more versatile control, but does not change the relationship between signal and load movement. The error signal to the amplifier may be either an a-c or a d-c voltage. Many servos in fire control equipment have an a-c error signal, while the amplifier and servomotor operate on d-c voltages. A typical example of this is the amplidyne power drive used to position antennas and directors. In this type of drive synchros supply a-c signal voltages which must be demodulated. Other servos in fire control equipment have a d-c signal voltage and an a-c amplifier and servomotor. In these servos the d-c signal must be modulated by the servo's a-c reference voltage. Modulation and demodulation are covered in Basic Electronics, NavPers 10087-A.

Comparison of A-C and D-C Servos

Generally speaking, a-c and d-c servos are similar. They both meet the basic requirements of a fire control servo and have essentially the same components. The type of servo used is determined by the requirements of the load. Heavy loads with a wide speed range, such as directors and radar antennas, are controlled primarily by d-c servos. Light loads with a fairly constant speed requirement are normally controlled by a-c servos. The characteristics of a-c and d-c servomechanisms will tell us why this is so.

A-C SERVOMOTORS.—Large a-c motors are too inefficient for servo use. To obtain the desired torque-speed output curve the motor becomes too large, draws excessive power, and is difficult to cool. Hence a-c servos in fire control equipment are used primarily to control light loads which require low power. Most of the a-c servomotors are of the two-phase or split-phase induction type. Fundamentally, these a-c motors are constant-speed devices, although their speed can be varied within limits by varying the amplitude of the voltage to one of the motor's stator windings.

The voltages to the stator windings of a two-phase motor should be exactly 90 electrical degrees apart. The 90° phase relationship can be established by shifting the phase of the voltage to either of the stator windings. Any phase shift that changes the 90° relationship will reduce the motor's efficiency. The direction of rotation of the motor can be changed by reversing the phase relationship between the stator windings.

D-C SERVOMOTORS.—The control characteristics of d-c servomotors are superior to those of a-c servomotors. The d-c servomotor can control heavy loads at variable speeds. Most of the d-c servomotors found in fire control equipment are either the permanent magnet type which are used for light loads, or the shunt field type which are used for heavy loads. The operational characteristics of these motors are covered in Basic Electricity, NavPers 10086-A. When they are used in servos, the strength of the motor's field which is supplied by the magnet or the shunt field is held constant. The direction and the speed of the motor's rotation is therefore determined by the armature current, which is supplied by the servoamplifier. An increase in armature current will increase the motor's speed. A reversal of the motor's armature current will change the motor's direction of rotation,

A disadvantage of d-c servoamplifiers is their tendency to drift. Drift is the low frequency variation of the output voltage with no change of the input. Drift is usually caused by changes in power supply voltages or by the change of component values due to temperature variations, aging effects, and humidity. Drift in d-c servoamplifiers can be overcome by circuit design. Frequently, however, an a-c amplifier is used and the output is demodulated. As a result, in some servos you may find modulation and demodulation stages which, on the surface at least, seem purposeless.

OPERATIONAL ACCURACY

A servo should drive rapidly toward the fixed correspondence point of a steady state or static signal. It should synchronize with a minimum of motion in the shortest time. Once synchronized, the servo should hold its position rigidly at the correspondence point. Where the input order signal is continuously changing position, the servo must drive to the correspondence point in the same manner as with a fixed signal. Once in correspondence, the servo must drive at the same rate as the input order signal. Since this is a position control servo, the rate of movement is established by the rate of displacement. Hence there is a definite lag between the order signal position and the output position.

The accuracy of a servo is determined by its ability to measure and produce an error signal and to amplify the error signal to a level which will move the load to eliminate the error. Hence the overall accuracy of a servo is determined by the accuracy of its components and their input data.

The error detector receives and compares the ordered position and the actual position of the servo's output. Any error in the input data will naturally reduce the accuracy of the error detector's output. The accuracy of the error detectors is determined by the amount of difference between its inputs that is necessary to produce a usable error signal.

The gain of the servoamplifier determines how large the error signal must be before amplifier output is sufficient to drive the error reducer. The higher the gain, the more sensitive the amplifier and the more accurate the servo. The efficiency of the error reducer determines how large the control current must be before it will drive.

The accuracy of the data, error detector, servoamplifier, and error reducer determine the static error or dead space of the servo. The static error is the angular displacement between the input and output of the servo under static conditions, (synchronized to a fixed order signal). The static error under load is the angular lag between the input and output of the servo when the input signal is moving at a constant velocity. The static errors are sometimes called steady state errors.

We have taken a negative approach to accuracy to show that servos have inherent sources of errors. Because of the errors, the term "null voltage" is used rather than "zero voltage," when the servo is synchronized. But do not get the false impression of large errors; the accumulative error in fire control servos is small. Multiple-speed data transmission systems are used to increase the accuracy of servos. Multiple-speed synchro systems are covered in chapter 7 of this text. Servos have high gain amplifiers to increase accuracy.

RESPONSE TIME

Fire control requires a servosystem to operate smoothly, rapidly, and with as few errors as possible. To obtain these operational characteristics, one quality is counterbalanced against the other. To increase the rapidity of response of the system to a signal, the gain is increased. This also tends to reduce error in the system. But a high gain or "tight" servo has a tendency to overshoot and oscillate, or, in other words, to be unstable. Response or synchronization time is the time the servo requires to settle down in synchronization to an order signal.

"HUNTING"

A servo will drive its load to the correspondence position. The servo's error signal and output torque are zero at correspondence, but due to the load's inertia it will continue to move. As the correspondence point is passed, the error signal tends to reverse the direction of movement. But a short time is needed to stop the load; and, during this time, the load will continue to move away from correspondence. When it does stop, the error signal will drive the load back towards correspondence. At correspondence the load has again acquired sufficient inertia to drive on past. The result is a series of overtravels of the correspondence point (fig. 8-10).

This condition is called "hunting", and is a characteristic which must be corrected in all

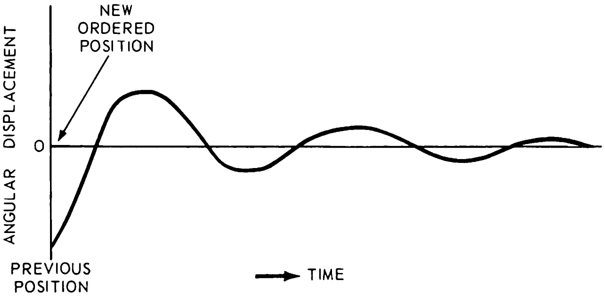


Figure 8-10.—Overtravels of the correspondence point.

servos. Obviously, hunting reduces the smoothness of the servo's followup action and increases its synchronization time. To overcome hunting, the servo must anticipate the load's inertia and its position with respect to the correspondence point.

When a servo is hunting, its oscillations about the correspondence are of a low frequency. A servo with a high gain amplifier has a tendency to oscillate at a high frequency with a low amplitude. The high frequency oscillations are started by some type of disturbance or variation such as random noise in the electrical section of the servo or lost motion in the mechanical section. Once the oscillations are started, the high gain of the amplifier tends to assist them, while the inertia of the load continues to reintroduce the error caused by the oscillation.

STABILIZATION

To obtain smoothness of operation, the system's gain is damped. Damping can be obtained by either introducing a voltage in opposition to the signal voltage or placing a physical restraint on the servo output. The function of damping is to reduce the amplitude and duration of the oscillations that may exist in the system. Every system has one or more natural oscillating frequencies which depend on the weight of the load, designed speed, and other characteristics.

DEGREE OF DAMPING

The degree of damping is determined by the required operating characteristics of the servosystem. If the system is OVERDAMPED, it will not oscillate about the correspondence point. However, due to the large amount of restraint placed on the servo, it will have a comparatively large dead-space or steady-state error. The overdamped servo will also take an excessively long time to synchronize (fig. 8-11).

On the other hand, the UNDERDAMPED servosystem will have instant response to an error signal. But it will have erratic operation due to the low amount of restraining force placed on the servo, and will oscillate or hunt about this point of synchronism. Somewhere between these two extremes, we can obtain adequate accuracy and smoothness plus a moderately short synchronizing time.

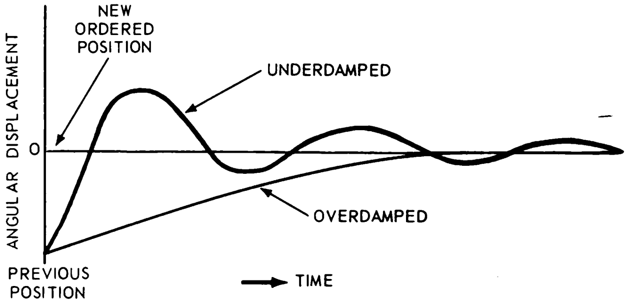


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Figure 8-11.—Degree of damping.

TYPES OF DAMPING

Viscous Damping

The simplest form of damping is viscous damping. This is the application of friction to the output shaft or load that is proportional to the output velocity. The amount of friction applied to the system is critical, and will materially affect the results of the system. The application of friction absorbs power from the motor, and this power is dissipated in the form of heat.

A pure viscous damper would absorb an excessive amount of power from the system. However, a system having some of the characteristics of a viscous damper, but with somewhat less power loss, is used in actual practice. The first damper of this type to be discussed utilizes a friction clutch to couple a weighted flywheel to the output drive shaft. A flywheel has the property of inertia.

FRICTION CLUTCH.—As the servomotor rotates, the clutch will couple a definite amount of this motion to the flywheel. The flywheel will gradually overcome its inertia and gain speed until it approaches the velocity of the motor. The flywheel in turning absorbs energy (power) from the servomotor. The amount of energy stored in the flywheel is determined by its velocity. Because of inertia, the flywheel will resist any attempt to change its velocity.

As the point of correspondence is neared and the error signal is reduced, the motor starts to slow down. The flywheel immediately releases some of its energy into the output shaft in an attempt to continue at the same speed. Thus the flywheel will cause a large first overtravel. The servosystem, to correct for this overtravel, reverses the direction of the motor. Once again the flywheel resists the motor movement and absorbs energy from the system. This drastically reduces the second overtravel and all subsequent overtravels of the motor. This effect dampens the oscillations about the point of correspondence and reduces the servosystem's synchronizing time.

The motor rotation is transmitted to the flywheel through the friction clutch. The inertia of the flywheel is an additional load on the motor. The friction clutch will slip with any rapid change of direction or speed. This slipping effectively disconnects the flywheel instantaneously, and thus governs the amount of power the flywheel will draw from the motor.

MAGNETIC CLUTCH.—Another type of viscous damper is the MAGNETIC or EDDY CURRENT damper. The magnetic damper is functionally similar to the friction clutch damper. The principal difference between the two is in the method of coupling the flywheel (inertia weight) to the servomotor output shaft. In the magnetic damper, the shaft and flywheel are coupled by a magnetic field, rather than a frictional contact. The coupling is made by the interaction of a magnetic field generated by a permanent magnet which rotates with the rotor of the servomotor and the induced eddy current in the flywheel.

The effect of viscous damping is shown in figure 8-12. The solid line shows the action of the load without damping. The time required to reach a steady-state condition should be noted. This time is greatly reduced with damping, although the initial overshoot is increased. Viscous dampers effectively reduce transient oscillations, but they also produce an undesirable steady-state error (velocity lag or position error). Since the friction damper absorbs power from the system, its use is normally limited to small servomechanisms.

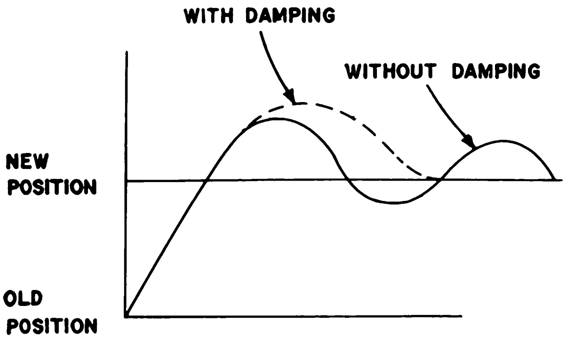

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Figure 8-12.—Effect of friction damper.

Error-Rate Damping

Since no physical device can respond instantaneously to a sudden force, there is a time lag between the signal input of a servosystem and its output response. To reduce this time lag, amplification is increased. We know that this also accentuates the tendency of the system toward instability. Viscous dampers act as part of the servo load, so they are not the answers to reducing the response lag. The answer lies in increased amplification with error-rate damping.

Error-rate damping consists of introducing a voltage that is proportional to the rate of change of the error signal. This voltage is combined with the error signal in the proper ratio to obtain optimum servo operation with negligible overshooting and oscillations.

The advantages of error-rate damping are:

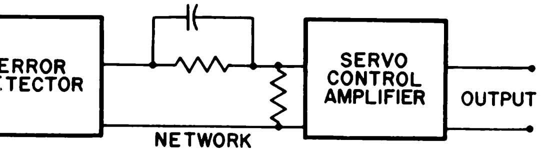
1. Maximum damping occurs when a maximum rate of change of error signal is present. This normally would occur when the servo load reverses direction. Obviously, this is when maximum damping action is required.
2. Since a CHANGE in the signal causes damping, there is a minimum amount of damping when no signal, or a signal of constant strength, is present. This means small steady-state errors.

Error-rate voltages are generated by either electromechanical devices or electrical networks in fire control equipment. An electromechanical device widely used to generate an error-rate voltage is the tachometer generator, commonly called a "tach." The rate generators previously described are tachs. The tach is mechanically coupled to, and rotates with, the servo's output shaft. Its output voltage is proportional to the output velocity of the servo. Since the voltage output is proportional to load velocity it is also proportional to the inertia of the load due to its velocity. Hence the output voltage can be fed back to the amplifier to indicate the load's velocity and therefore its inertia.

ELECTRICAL ERROR-RATE VOLTAGE NETWORKS.—Electrical networks used for error-rate damping consist of a combination of resistors and capacitors forming an RC differentiating network. From your study of basic tricity, you know that a differentiating circuit uces an output voltage that is proportional ne rate of change of the input voltage. In an ircuit, if the voltage across the resistor is as the output, it is referred to as a DIF-ENTIATOR (fig. 8-13), and, if the voltage ss the capacitor is the output, it is referred an INTEGRATOR (fig. 8-14).

ervos used in fire control equipment are ired to follow an input signal which is some- s changing at a constant rate and sometimes variable rate. A director's train power e is an example of a servo whose input al may be fixed, changing at a constant rate, t a variable rate. When the director is king a target on a steady course and speed, train rate may be constant. However, if the et changes course or speed the director drive may require a sudden acceleration. n be seen that this servo must adapt itself variety of signal types, and respond to them substantially zero error.

et's use the integrator circuit shown in e 8-14—or, as it is sometimes called, an ral control—to explain error-rate damping. integral control circuit is shown in its lest form. It is made up of a combination wo resistors and a capacitor. Notice that etwork is in series with the error detector the amplifier. The circuit is designed for signals; if the error detector puts out an signal, it must be demodulated before it rs the network. The signal is dropped across nd the R_1, C_1 leg of the network. The R_1, C_1 leg is in parallel with the amplifier's input circuit. Therefore, only that portion of the signal developed across the R_1, C_1 leg is fed into the amplifier. R_2 is in series with the leg and is larger than R_1. Briefly, here is how the circuit works.



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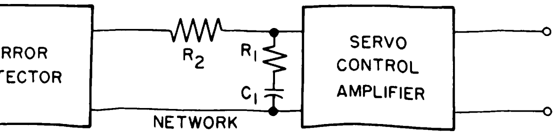
re 8-13.—Error-rate stabilization network.



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ure 8-14.—Integrator used as an integral stabilization network.

Assume that the error signal is steady or changing slowly. Initially, all of the constant error voltage is divided between R_1 and R_2. But the longer the error voltage is applied, the more C_1 charges up. The increasing voltage drop across C_1 adds to the drop across R_1. Since these two components are in parallel with the amplifier, their combined voltages will appear at the input terminals of the amplifier. In effect, the servo will overcorrect the error signal and the output shaft will catch up with the input signal. As the drive increases its velocity it will reduce the error signal. The capacitor C_1 will start to discharge and oppose the reduction. The damping action of the capacitor's charging and discharging voltages, which oppose the changes in the error signal, will assist the servo to settle down quickly at the new velocity.

This discussion of an integral control is by no means complete. There are many types of RC circuits and many different applications of their use for error-rate damping in servos. The discussion does cover the fundamental operation of an electrical RC network which can provide error-rate damping. A more detailed coverage will be given in a later text of this series of training courses.

POSITION SERVOS IN FIRE CONTROL

The fire control problem is a geometric problem dealing with angles, reference planes, and lines, and vectors representing motions and forces. Elements in the equipment used to measure or compute these quantities must be positioned accurately to solve the problem of hitting a target. For example, if we are to compute the wind effect on a projectile we must establish the wind vectors with respect to the line of fire. The primary concern in the example is the position of the two quantities. Naturally, position servos would be used to control these computing elements. Hence there are many position control servos in fire control equipment. Some examples are:

1. Director or radar antenna power drives in the designation mode of operation. In this mode the director established the position of the target.

2. Position control of computing elements except those which deal with the dynamic generation of the time rate of change of a quantity.
3. Position control of stabilization quantities such as level and cross level.

VELOCITY SERVO ACCURACY

In the velocity servo shown in figure 8-4, when the output voltage of the response rate generator is equal and opposite to the signal rate generator's output voltage the load is moving at the correct velocity. The accuracy of the servo is measured by the difference in velocity between the input shaft and the output shaft. Since in all servos an error must exist before a correction can be made there is a certain amount of lag in the servo's output velocity. The amount of lag is determined by the accuracy of the rate generators, the servo's detecting devices which furnish the servo with its operational data, and the sensitivity of the servo to an error. We can increase the sensitivity of the servo to reduce the lag by increasing the gain of the amplifier. But if we oversensitize the servo, it will become unstable. The load will alternate between leading and lagging the correct velocity, and an almost continuous acceleration would occur. Thus, as in position servos, we accept a small error (velocity lag) to obtain smoothness of operation.

In the elementary servo shown in figure 8-4 no means were provided to measure shaft position. But in most applications the position of the output is as important as its velocity. Therefore a position sensing device is normally used as a signal source in velocity servos. We could obtain the same results with a CT by turning its rotor as a function of time, that is, so many degrees per second, as we did with the rate generators. As you rotated the handcrank there would be a timed velocity. Hence the accuracy of the servo is measured by how close the servo's output follows a movement from a position already established. This is referred to as the servo's dynamic fidelity.

Stability in velocity servos is obtained by damping in much the same manner as in position servos. However, there is a zero velocity lag when the servo is static and maximum velocity lag when the servo is driving at maximum speed. Hence velocity lag is a dynamic error proportional to velocity. This error will result in a position error. In a servo where the rate (velocity) is very high, the position error due to velocity lag would be excessive. In such a servo a derivative circuit could be used to provide an output proportional to changes in its input voltage. Since the input voltage is proportional to velocity the output of the derivative circuit (fig. 8-13) is proportional to a change in velocity or an acceleration. A derivative circuit is a differentiating circuit.

Velocity servos are used in equipment requiring an output velocity corresponding to an input voltage. Their use in fire control equipment is mainly in the target tracking loop. The director and radar antenna power drives are velocity servos when they are in the automatic tracking mode of operation. Computing elements used to generate target position in the computer are controlled by velocity servos. Many of the gun mount's and missile launcher's power drives follow the fire control computer signals as velocity servos. An example of a velocity servo in a fire control director is covered in the next chapter.

CHAPTER 9

FUNDAMENTALS OF GYROSCOPES

The purpose of this chapter is to provide you with basic information on gyroscopic principles and the applications of gyroscopes in fire control equipment. Emphasis has been placed on basic fundamentals and functions of gyroscopes, rather than on details of construction, repair, and maintenance. These details will be covered in later training courses.

The gyroscope, commonly called a gyro, has existed ever since the first electron was sent spinning on its axis. Yes, electrons spin and show all the characteristics of a gyroscope. And so does the earth, which spins about its polar axis at high speed. It is interesting to note that any point on the equator travels at a speed of over 1000 miles per hour, which is about three times as fast as the gyros you are going to work with.

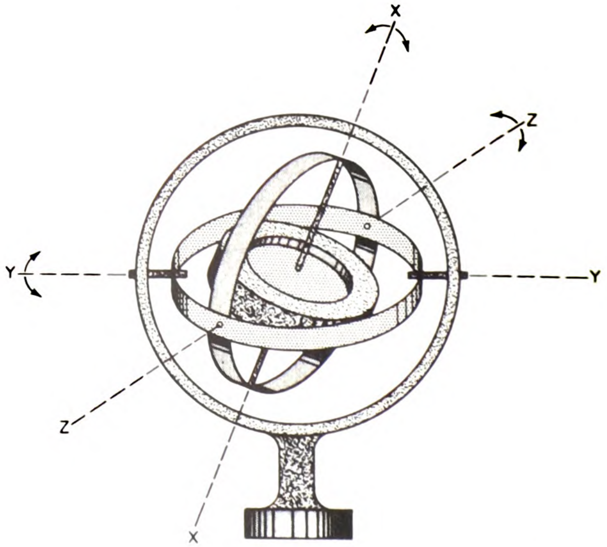
WHAT IS A GYROSCOPE?

Any rapidly spinning object—a top, wheel, an airplane propeller, or a spinning projectile—is fundamentally a gyroscope. Strictly speaking, however, a gyroscope may be defined as a mechanical device containing a spinning mass which is universally mounted, that is, mounted so it can assume any position in space. Figure 9-1 shows a model of a gyro. As you can see, a heavy wheel is mounted so that its axile (spin axis) is free to turn in any direction. The wheel can spin about axis x, it can turn about axis y, and finally turn about axis z. With this mechanical arrangement the spinning wheel can assume any position in space. Thus our model gyro meets the requirements of the definition.

How It Got Its Name

The word gyroscope was first coined by the French scientist, Leon Foucault, in 1852. Foucault made his first gyroscope for the purpose of demonstrating the rotation of the earth. The word gyroscope is derived from the Greek words "gyro," meaning revolution and "skopein," meaning to view. Combined, the term means "to view the revolution of the world."

Although Foucault lived over one hundred years ago, there was at that time no completely satisfying demonstration of the theory that the earth was a rotating body. There were people who still clung to the idea that the earth stood still and the sun, moon, and stars moved around it. Foucault wanted to demonstrate the earth's rotation by something on the earth itself. He mounted a wheel in a frame on very delicate bearings so that it could maintain its spinning axis in a fixed direction. He was able to show that the earth did revolve in relation to the fixed direction of his experimental gyroscope. Because his new instrument made the rotation of the earth visible, he combined the two Greek



12.137
Figure 9-1.—Gyro model, universally mounted.

terms mentioned above and called the instrument a gyroscope.

Basic Properites of Gyroscopes

Gyroscopes have two properties which make them useful in fire control:

1. The axis of rotation (spin axis) of the gyro wheel tends to remain in a fixed direction in space if no force is applied to it.
2. The axis of rotation has a tendency to turn at a right angle to the direction of an applied force.

The idea of maintaining a fixed direction in space is easy to show. When any object is spinning rapidly, it tends to keep its axis pointed always in the same direction. A toy top is a good example. As long as it's spinning fast, it stays balanced on its point. Because of its gyro action, it resists the tendency of gravity to change the direction of its axis. You can think of many more examples. A bicycle is easier to balance at high speed than when it's barely moving. At high speed, the bicycle wheels act as gyros, and tend to keep their axes parallel to the ground.

(Note that it's easy to MOVE the axis as long as you keep it pointing in the SAME DIRECTION. The gyro resists only those forces that tend to change the direction of its axis. In a bicycle, since the axis of rotation is horizontal, the wheels will resist any force that tends to tilt the axis, or turn it.)

Any wheel that's spinning fast will show gyro action. The heavier the wheel, and the faster it is spinning, the stronger the gyro action. You can make this action stronger by concentrating the weight of the wheel near its rim.

If you can get hold of a gyroscope top, like the one in figure 9-2, you can do some instructive experiments with it. Hold your gyro top with its axis vertical, as in figure 9-2, and start it spinning. As long as it is spinning fast, it will stay balanced. You can balance it on a string or on the point of your finger; the axis will stay vertical as long as the top is spinning fast.

Now stop the gyro top and turn its axis horizontal. Start it spinning again and balance one end on a pivot, as in figure 9-3. What happens now? If the top is spinning fast, it won't fall. Its axis will stay horizontal, resisting the tendency of gravity to change its direction. But while the gyro will resist the force that gravity applies to it, it will still RESPOND to that force. And it responds by moving its axis at a RIGHT ANGLE to the APPLIED force.

Figure 9-4 is another view of the same gryoscope. Its far end is still balanced on the pivot. Gravity is pulling down on the near end of the frame. If the gyro rotor is turning in the direction shown by the arrow, then the near end of the frame will turn to the left. (If the rotor is turning in the opposite direction, the frame will turn to the right.) The axis will stay horizontal, but the gyroscope will respond to the force of gravity by rotating around the pivot.

We can summarize gyro action like this: A spinning gyro tends to keep its axis pointing in the same direction. This is called rigidity. If you apply a force that tends to change the direction of the spin axis, the axis will move at a right angle to the direction of the force. If the axis is horizontal, and you try to TILT it, the axis will turn. If the axis is horizontal, and you try to turn it, the axis will tilt. This second characteristic of a gyro is called precession.

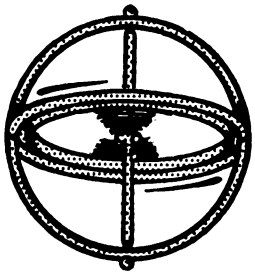


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Figure 9-2.—A gyroscope top.

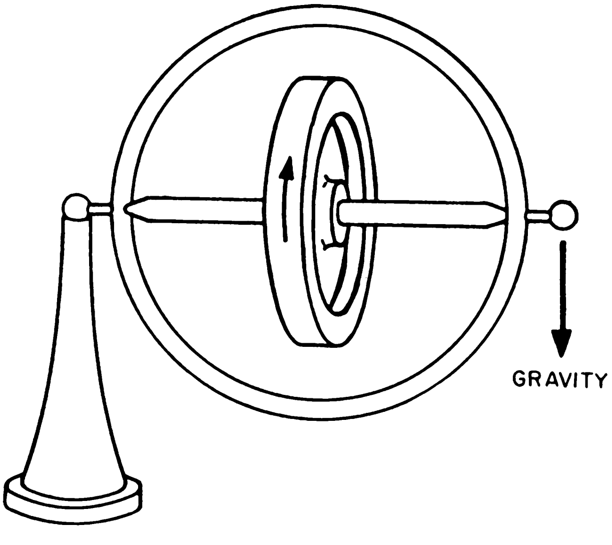

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Figure 9-3.—Gyro top with axis horizontal.

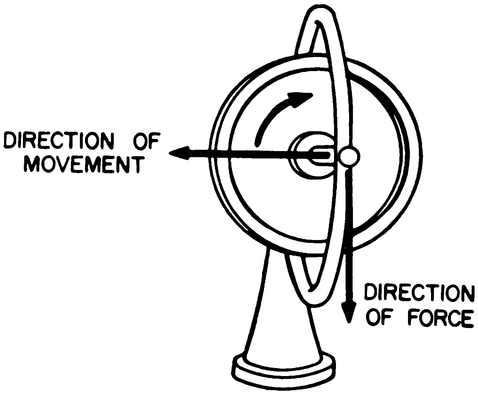

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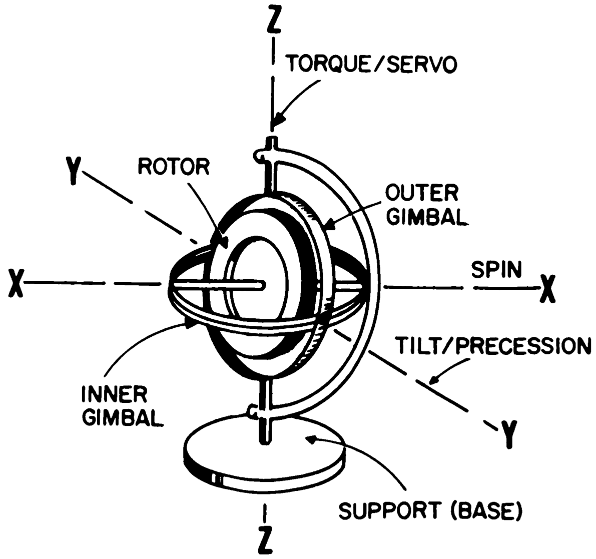
Figure 9-4.—Gyro precession.

Basic Gyro Elements

The gyro shown in figure 9-5 is a basic universally mounted gyro. The components are: Rotor, inner gimbal, outer gimbal, and base or support. The three major axis of any gyro are the spin, torque or servo, and precession. The spin axis is, of course, the axis on which the rotor spins. The torque or servo axis is the axis about which the disturbing force is applied, whether it is a desirable or undesirable force. The precession or tilt axis is the axis the gyro turns about as a result of the force applied to the torque axis.



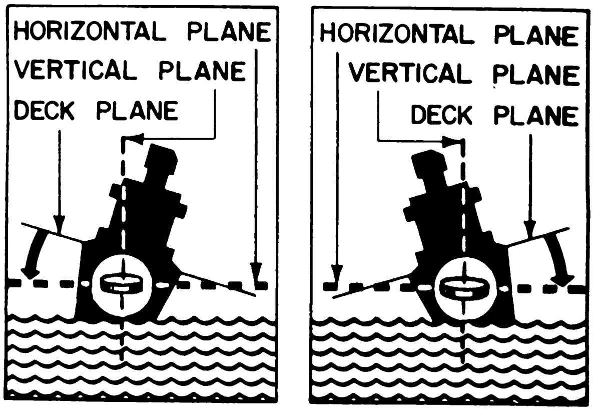
12.138
Figure 9-5.—Basic universally mounted gyro.

The term gimbal may be defined as a device for permitting a body to incline freely in any direction and retain that position when the support is tipped or repositioned. Note that in figure 9-5 the support may be moved about all three axes without the rotor position being disturbed. Ridigidy in space is clearly shown in fundamental form by this demonstration.

Where Gyros are Used

Gyros, because of their unique properties, are used in all fire control systems. A gyro is capable of measuring the angular displacement of its support mounting from its spin axis or reference plane. Because the spin axis of the gyro is fixed in space, the gyro can provide stabilized reference planes from which the various angles, lines, and motions in the fire control problem can be measured. In figure 9-6 the gyro represents the stabilizing unit of a fire control system. The gyro, due to its rigidity, is unaffected by the ship's roll and pitch. In a manner of speaking, the ship is rolling about the gyro. The gyro measures the angular displacement of the deck plane out of the horizontal plane, which is parallel to the spin axis. Corrective signals that are a measure of the displacement are generated to obtain a stabilized problem.

In the days of wooden ships a simple pendulum was used to measure the ship's motion with respect to the earth. The pendulum was suspended so that it was free to align itself with the earth's gravitational pull. By watching the swing of the pendulum the gun battery could be fired at any desired point in the ship's roll. Today,



12.139
Figure 9-6.—A stable element establishes the vertical and horizontal planes.

however, the gyro is used for stabilization. Later on in this chapter we will discuss a stabilizing unit, the Stable Element Mk 6, in more detail.

A gyro can be used to determine the angular velocity of its support mounting about a reference plane. Since a gyro will precess when acted on by an external force, we can use this property of a gyro to obtain angular velocity. For example, a special type of gyro can be mounted in a director so that the angular motion of the director is a force acting on the gyro. The gyro will precess an amount directly proportional to the angular rate of the director's motion. We will cover this type of gyro, the rate gyro, later in this chapter.

Gyros have many applications in a varity of fields. In chapter 3 we mentioned their use in guided missiles. Their applications are not confined to ordnance equipment. The gyrocompass, submarines' inertial navigation systems, and aircrafts' autopilots and horizon indicators all use gyros.

Gyroscopic properties are not always desirable. Take, for example, an aircraft which has high speed rotating components. These components will exhibit gyroscopic rigidity; still an aircraft must be highly maneuverable. Hence the rotating components are installed so that their rigidity has the least effect on the aircraft maneuverability.

RIGIDITY

As you know, a gyroscope is a spinning body that tends to keep its spin axis rigidly pointed in a fixed direction in space. What do we mean by FIXED DIRECTION IN SPACE? A fixed direction on earth is by no means fixed in space, because the earth turns once on its axis every 24 hours. It makes a complete revolution around the sun every year. And the sun itself is moving, taking the earth and the other planets with it. Because of these motions, the expression "fixed direction in space" as used here is theoretical. If that were an exact statement, our universe would have to be unaccelerated and therefore nonrotating. But for all practical purposes we can say this: A line from the earth to a distant star is a fixed direction in space, (fig. 9-7). If the spin axis of a spinning gyro is pointed at a distant start, it will remain on the star as the earth turns.

Any rapidly spinning body has the property of rigidity. A wheel spinning on its axis is in effect a gyro, and offers resistance to any attempt to tilt it from whatever position it has assumed in space. The gyro rotor is not rigid as we think of a tree—it can be moved in several ways—that is to say it can be moved freely from one place to another with the gyro offering little or no resistance so long as the movement is parallel to or perpendicular to the plane of the spin axis. This is called translation. On the other hand, when we have a rotor spinning on an axis and we try to tilt it, it offers resistance, and this resistance is in proportion to the effective weight of the spinning body and the speed at which it is spinning.

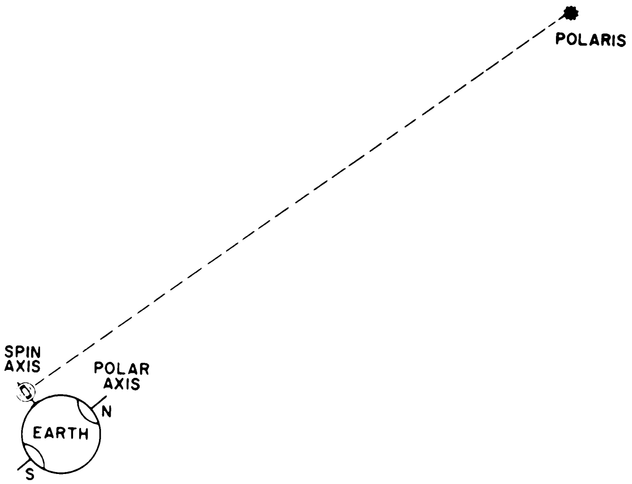


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Figure 9-7.—A gyro on the earth pointing in a fixed direction in space.

Three factors determine a gyro's rigidity, or the strength whith which it resists any external force tending to displace its rotor spin axis. These factors are: Weight of its rotor, distribution of this weight, and rotor speed.

We can consider the gyro as an enclosed mechanical system. The energy in the system is equal to the input energy. Hence the torque necessary to spin the gyro rotor is contained in the rotor as angular momentum. Momentum is the energy in a body due to its velocity. The heavier the gyro rotor, the larger the torque necessary to spin it, and the greater the angular momentum of the rotor. If we have two rotors with identical shapes but of different weights spinning at the same velocity, the heavier of the two will be more rigid in its spin axis since it contains the greater angular momentum and, as will be explained next, the greater inertia.

To understand the effect of weight distribution in a rotor of a gyro, consider two rotors of the same weight, with the diameter of one, half at of the other. Now, when we spin both of ese rotors at the same speed, we find that the otor with the greater diameter is much more gid than the one with the smaller diameter. ext we find that we can make both rotors equally gid by causing the rotor with the smaller diam- er to spin faster than the larger rotor. Thus gidity is dependent upon both speed and dis- ibution of weight. The weight of the larger otor being farther away from the axis of spin uses it to be more effective for rigidity. In ysics it is said that the weight of the larger ameter rotor has the greater "moment of in- rtia." What is moment of inertia? First, let's nsider inertia.

INERTIA is a fundamental property of matter. othing in nature will start or stop moving by self. Some external force must be applied to first. For example, you have felt the tendency fall backwards while standing in a bus which arted suddenly. What happened was that your dy tended to remain stationary but your feet ere carried forward with the moving bus. From is experience you can come to the conclusion at when a body is at rest it will tend to remain rest. After you regained your balance and ur body started moving at the same speed and rection as the bus, everything was fine. Fine at is until the driver suddenly stopped the bus. gain you lost balance and tended to fall forward. this case your body tried to continue in the rection in which the bus was traveling, but your et were retarded by the stopping bus. From is experience we can conclude that a body in otion will tend to follow in the same straight ne or direction unless acted upon by some ex- rnal force. The two experiences mentioned e examples of Sir Isaac Newton's first law of otion which states: A body at rest remains rest, and a body in motion continues to move a constant speed along a straight line, unless e body is acted upon in either case by an un- lanced external force. Newton's first law of otion applies equally well to rotating bodies. onsider for a moment the spinning rotor of a ro. Every particle of matter in the gyro rotor trying to move in a straight line; but the cir- ılar structure of the wheel prevents this, and ılls them all into a circular path. The particles eep trying, nevertheless, to stay in as straight line as possible. Consequently the rotor keeps otating in the same plane unless acted upon by me outside force. If no external forces are esent, the wheel will not move from its plane of rotation. Common sense tells us that if this is so, the spin axis must remain fixed.

Moment of Inertia is a measure of the torque needed to bring about a change in the motion of a rotating body. Moment is defined as the tendency of energy acting on a body to produce motion, while inertia is the tendency of a body to resist a change in motion.

MOMENT OF INTERTIA can be demonstrated with two weights—one heavy and the other light, a board, and a fulcrum, arranged in the manner of a seesaw. To balance the two weights, we have to place the heavy weight near the center and the light weight near the end of the board. This makes the light weight more effective by being farther out from the fulcrum and having greater leverage. If we have two equal weights, we can make one outbalance the other by putting one farther out on the board. The same principle applies to two rotors of equal weight, the rotor having its weight distributed "farther out on the board" has the greater moment of inertia. Its weight is more effectively placed and makes the wheel more rigid in space.

Now we can conclude that a gyro resists any tilting force, and that the amount of resistance depends upon the weight, distribution of the weight, and the speed of the rotor. If we were to design a gyro for maximum resistance to an external force we would make it as heavy as possible, put as much weight as far as possible from the center of rotation, and spin the gyro wheel as fast as possible. As long as the gyro and gimbal bearings were frictionless and the center of gravity of the wheel was at the intersection of the three major axes, no displacement of the support of our perfect gyro could change the position of its rotor in respect to space. This property of a gyro is variously called rigidity, rigidity in space, rigidity of plane of rotation, gyroscopic inertia, or stability, to name a few of the more common terms. All of these terms mean the same thing.

PRECESSION

A gyro is a true space device in regard to its ability to maintain its axis in a fixed direction. To provide useful information its spin axis must be related to some reference, usually the earth's surface. This is done by using the second fundamental property of a gyro—precession. The gyro is precessed until its spin axis is pointed in the desired direction. So far we have covered precession in very general terms.

Let's consider this action in more detail and relate it to a specific equipment—the Mk 6 stable element.

Precession can be shown very plainly by using the models shown in figure 9-8, which resemble the Mk 6 stable element gyro and its gimbal mounting. A gyro wheel (rotor) is mounted so that is is free to align its spin axis in any direction. Here the wheel rotates in a flat loop called the gyro case (in some applications it is called the inner gimbal). The gyro case is pivoted in a ring—the gimbal ring—and the gyro can swing about the Z axis. The gimbal ring itself turns on pivots which connect it to the fork (support), permitting the gyro to tilt from side to side. This type of mounting is called a GIMBAL MOUNTING. Regardless of how the fork is placed, the spinning gyro wheel is free to lie in any given plane. That's why it is called a free gyroscope in this mounting.

To show the effect of precession, push down on the gimbal ring at point A at the nearer end of the z-z axis (fig. 9-8A). You would expect the ring to tilt around the y-y axis.

But here's the surprise—instead of rotating about the y-y axis as you might expect, the gyro case will turn about the z-z axis. You can see the effect of precession in figure 9-8B.

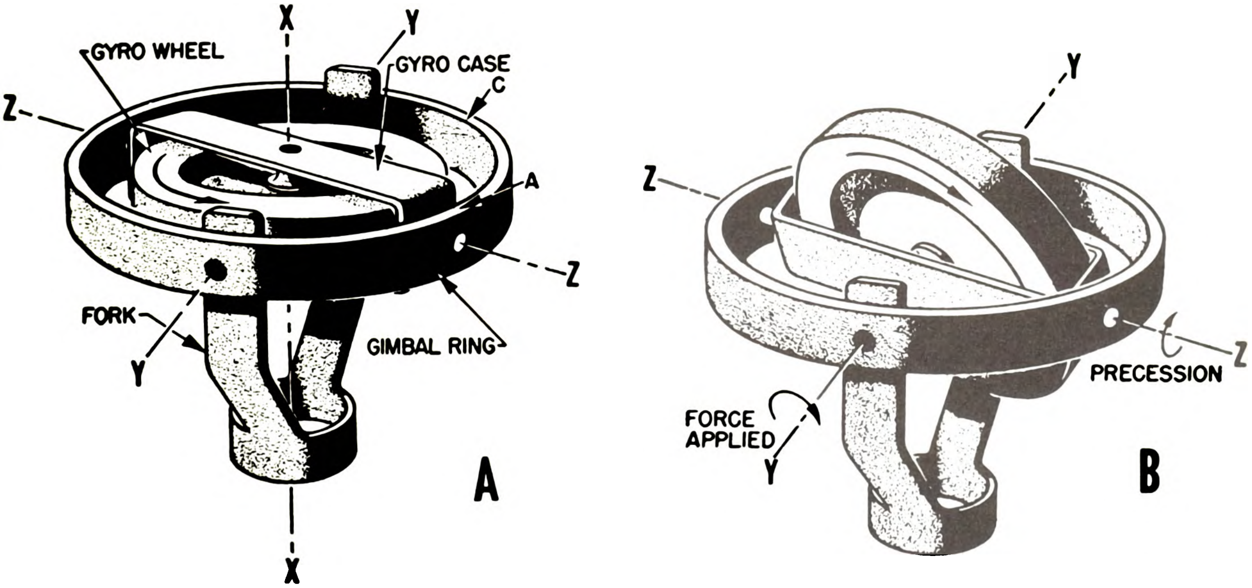
Similarly, going back to figure 9-8A, suppose you push sideways on the top of the x-x axis (the spinning axle of the gyro), trying to rotate the wheel around the z-z axis. Then, instead of rotating about the z-z axis, the gimbal ring will turn around the y-y axis.

If you push down at point C on the gimbal ring (fig. 9-8A), midway between the y-y and z-z axes, you will find that the gimbal ring rotates around the y-y axis, and that the gyro case rotates around the z-z axis. The total effect causes the gyro wheel to turn around a line lying from point C through the center of the gyro wheel.

Now for the next question: In which direction will the gyro precess? There's a simple rule that tells you. It depends on the direction of SPIN of the gyro and the direction of the applied FORCE.

Here's a rule that applies to all spinning gyros: THE GYRO WILL ALWAYS PRECESS AT RIGHT ANGLES TO THE DIRECTION OF THE APPLIED FORCE.

Look at figure 9-8A again. If you keep pushing down on the gimbal ring at point A, the gyro



A. Gimbal mounting
B. Precession

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Figure 9-8.—Gyro action.

case will keep turning until the axle of the gyro wheel is horizontal. Then there will be no further precession. At that point the gyro wheel is spinning in the same direction in which the applied force is pushing.

Here's another rule: A GYRO ALWAYS PRECESSES IN A DIRECTION TENDING TO LINE ITSELF UP SO THAT ITS ROTOR SPINS IN THE SAME DIRECTION THAT THE APPLIED FORCE IS TRYING TO TURN IT. In other words, the spin axis chases the torque axis. When the two come into coincidence, precession no longer takes place.

Be sure you understand that most forces, when applied to the gyro mounting, do not cause precession. For instance, you can swing the fork around in any direction, and the motion will merely be taken up in the y-y and z-z axes. Similarly, a force applied lengthwise along one of the axes will have no effect. ONLY THOSE FORCES TENDING TO TILT THE GYRO WHEEL ITSELF WILL CAUSE PRECESSION. Thus you can see that if the base of the fork were attached to the deck of a ship, the gyro would have no tendency to precess as the ship rolled and pitched.

Let's consider further the important characteristic of gyroscopic precession, using another method to illustrate this fundamental property. As you know, the rigidity of a gyroscope may be increased by making the wheel heavier, by causing it to spin faster, or by constructing it so that a larger portion of its weight is concentrated near the circumference. As it is impossible to make bearings entirely free of friction, in most gyros friction is kept to a minimum, and the rotors are designed to have a great deal of rigidity. Whatever friction remains is small in comparison to the great rigidity of the heavy, rapidly spinning rotor, is that its effect upon the operation of the gyro is extremely slight.

An operating gyro will resist a force which attempts to change the direction of its spin axis, but it will move in response to such a force or pressure. The movement is not a direct one in response to the force; it is a resultant movement. The gyro axis will be displaced, not in the direction of the applied force, but in a direction at right angles to the applied force, and in such a way as to tend to cause the direction of the rotation of the rotor to assume the direction of the torque (rotational effect on a body, a twisting effect) resulting from the applied force.

For a given force, the rate of precession is governed by the weight, shape, and speed of the wheel. These factors are the same as those that determine the rigidity of a gyroscope. Therefore, it is reasonable to assume that there is a relationship between the rigidity of a gyroscope and the rate at which a given force will cause it to precess. Such a relationship does exist. The greater the rigidity of the gyroscope, the more difficult it is to cause precession, and the less the precession for a given force will be.

The direction of precession in response to an applied force depends upon the direction in which the rotor is spinning. The precession is in such a direction that the wheel turns, through the smaller distance, toward a position in which the force would be acting about the spinning axis, in the direction of the spin.

The forces acting on a gyrscope may be represented graphically as acting on the rotor itself, spinning freely in space, with a plane containing each of the axes of freedom.

For example, when a force is applied upward on the inner gimbal, as shown in figure 9-9, the force may be visualized as applied in an arc about axis y-y until it contacts the rim of the rotor at F, as in figure 9-10A. The effect produced by the force is equivalent to that produced by a force applied upward to the inner gimbal. The force at F is opposed by the resistance of gyroscopic inertia, preventing the rotor from being displaced about axis y-y. With the rotor spinning clockwise, the precession will take place 90° ahead in the direction of rotation at P, as in figure 9-10A. The rotor turns about axis z-z in

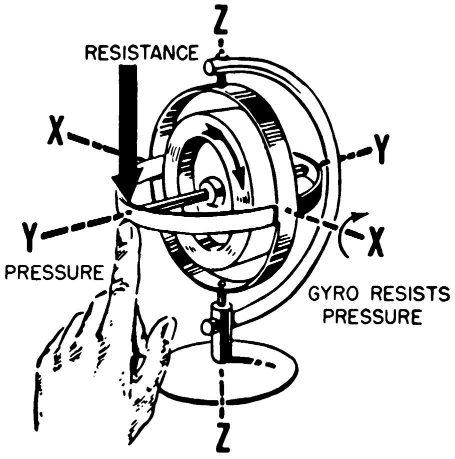

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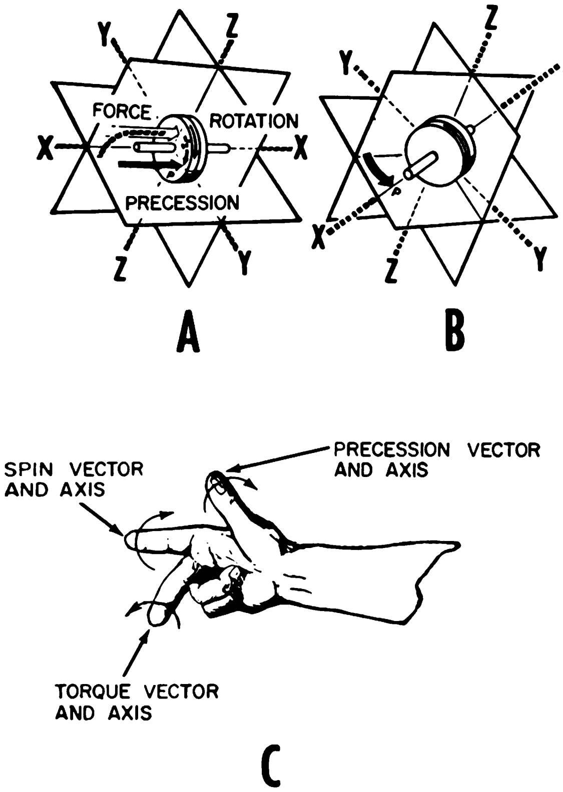
Figure 9-9.—Force applied to a gyro.



A. Direction of precession
B. Precessional movement
C. Hand rule to determine
direction of precession

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Figure 9-10.—Rules of precession.

the direction of the arrows at P, as in figure 9-10B.

Hand Rules

The motions of a gyrsocope can be analyzed by three basic vector quantities: (1) Spin, the angular velocity of the gyro rotor, (2) Torque, the rotary motion applied to change the direction of the rotor axis, and (3) Precession, the resulting angular velocity of the rotor axis when torque is applied.

All three motions are rotary (angular) and can be represented by vectors which point in such a direction that when looking in the direction of the vector the rotary motion is clockwise.

A convenient rule for determining the direction of procession is by the use of the fingers of the right hand. This method will not be new to you because you used a similar means to demonstrate the motion of a conductor in a magnetic field when you studied Basic Electricity, NavPers 10086-A.

The three vectors listed above may be represented by arranging the thumb, forefinger, and middle finger of the right hand mutually perpendicular as shown in figure 9-10C. The thumb points in the direction of the precession vector, the middle finger points in the direction of the torque vector, and the forefinger points in the direction of the spin vector. You can consider these vectors as the axes about which angular motion takes place. If you look in the direction of the pointed fingers and thumb you can visualize that all the rotary motions are clockwise as indicated in figure 9-10C.

The three-finger rule is useful for analyzing any gyroscope motion problem because if the directions of any two of the three vectors are known, the direction of the third vector can be found. Thus, the rotary motion around this vector may be determined, for facing in this direction the rotary motion is clockwise.

Another hand rule determines the direction of the spin vector. Curve the fingers of the right hand in the direction in which the rotor is turning, as if you intended to grasp it. The thumb will point in the direction of the spin vector. A similar rule will give you the direction of the torque vector. With the fingers of the right hand wrapped in the direction of the applied torque (the direction of the gyro would rotate if the rotor were not spinning) the thumb points in the direction of the torque vector.

Degrees of Freedom

A gyro can have two different degrees of freedom, depending upon the number of gimbals in which it is supported and the way the gimbals are arranged. You must not confuse the term "degrees of freedom" with an angular value such as degrees of a circle. The term as it is applied to gyros is an indication of the number of axes about which the rotor is free to precess.

A gyro mounted in two gimbals usually has 2 degrees of freedom. When two gimbals are employed it is said to be universally mounted. This arrangement provides two axes about which the rotor can precess. These two axes and the spin axis intersect at the center of gravity of the rotor which is also the center of gravity of the entire system (excluding the support). Thus the force of gravity does not exert a torque to cause precession. The rotor, inner gimbal, and outer gimbal are all perfectly balanced about the three principal axes. Actually it is impossible to have absolute freedom about them because even the most perfect bearings have some friction. But friction can be reduced to such a degree that it is slight in comparison to other factors. The gyro is capable of assuming and maintaining any position in space. Consider a rubber ball in a bucket or water. Even though the ball is supported by the water, it is not restricted as to attitude by the water but can lie in any attitude. If such a gyro were mounted in a ship, director, or a guided missile, it would not be affected by any of their movements. It would float inside its mountings much as the rubber ball floats in a bucket of water.

A gyro enclosed in one gimbal usually has one degree of friction, freedom of movement back and forth at a right angle to the spin axis. You should know something about the application of gyros in a guided missile, so let's put one of these one-degree-of-freedom gyros in a missile and observe its operation. We will mount it so that its axis of spin is parallel to the axis of travel of the missile. It is mounted now much like the flywheel in an automobile. It is spinning, and we have mounted it so that it can swing right to left. We can say that it has one degree of freedom. If the missile should nose up or down, the gyro would be forced to move exactly as the missile does (translate) in these directions. However, if the missile should turn left or right, the gyro would not change its attitude since it has freedom of motion in these directions. The spin axis would be fixed in the original direction of missile flight.

Sometimes you will read in OP's or hear about 3-degrees-of-freedom gyros. Don't let this terminology confuse you. It results from counting the spin axis as a degree of freedom about which the rotor can rotate.

Effect of Rotation of the Earth

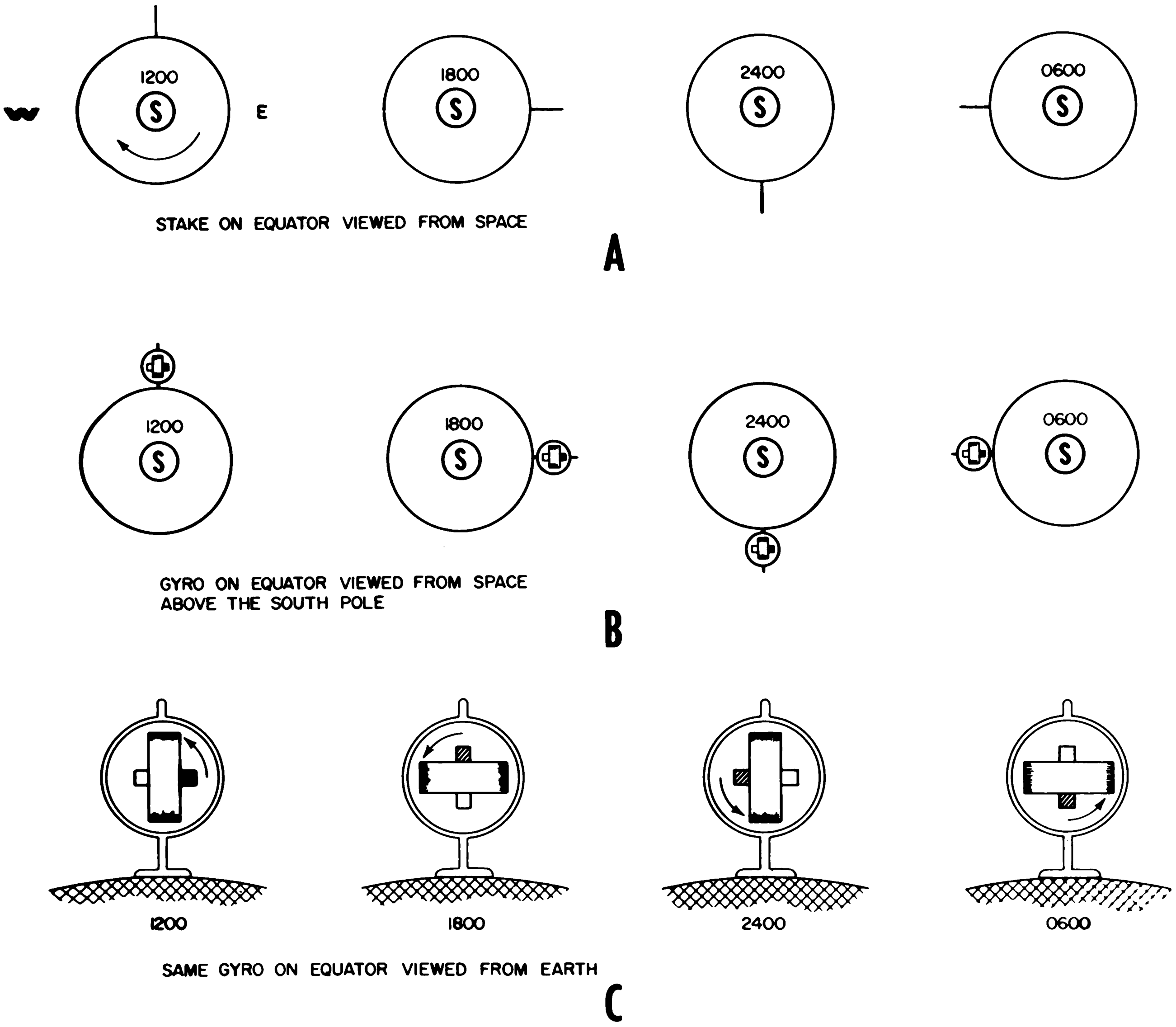
A free gyro maintains its axis fixed in space, and not in relation to the earth's surface. To understand this, imagine yourself in a space ship somewhere out in space and looking at the South Pole of the earth. You could see a sphere rotating clockwise, with the South Pole in the center. Maneuver your ship until it is on a direct line with the South Pole and then cut in the automatic controls to keep it in this position. The sphere you see would make a complete rotation every 24 hours.

You could keep track of that rotation by driving a big post into the Equator as shown in figure 9-11A. If this post was upright at 1200, the earth's rotation would carry it around so that it would be horizontal and pointing to the right, or east, at 1800. Likewise, the earth's rotation would carry the post around so that at 2400 it would be upside down. Then, at 0600 the next day, the post would be horizontal and pointing left, or west. Finally at 1200 the next day the post would be back in its original position, having been carried, with the earth, through its complete rotation. Notice that the post has many positions as you observe it—because it is attached to the earth's surface and does not have rigidity in space.

If you put a gyroscope in place of the stake you would see a different action. Imagine, now, a gyroscope instead of a post mounted at the Equator. The gyro is spinning and DOES HAVE RIGIDITY IN SPACE. Look at figure 9-11B. At 1200 the spinning axis is horizontal with respect to the earth's surface. At 1800 the spinning axis is vertical with respect to the earth's surface; but the gyro is still spinning in the same plane as before, and the black end is pointing away from the earth's surface. At 2400, the spinning axis is again horizontal. At 0600 the spinning axis is again vertical, and the black end points toward the earth. Finally, at 1200 the next day, the gyro is in the same position as when you started. In fact, the gyro wheel spinning on its axis has not changed the direction in space of its plane of spin in being carried through the whole rotation of the earth. This is because the gyro is RIGID IN SPACE.

You have just imagined observing the gyro from space. Now, let's come back to earth and stand right next to the gyro. You can't feel or see the earth's rotation—but it's rotating. Look at the gyro in figure 9-11C. From your viewpoint on earth, the spinning axis appears to make one complete rotation in one day. Actually, as you know, the gyro is rigid and both you the earth are rotating.

The effect on a gyro of the earth's rotation is sometimes called APPARENT DRIFT, APPARENT PRECESSION or APPARENT ROTATION.


W
E
1200
1800
2400
0600
S
STAKE ON EQUATOR VIEWED FROM SPACE
A
GYRO ON EQUATOR VIEWED FROM SPACE
ABOVE THE SOUTH POLE
B
SAME GYRO ON EQUATOR VIEWED FROM EARTH
C

A. Post on the Equator viewed
from space
B. Gyro on Equator viewed
from space
C. Gyro on Equator viewed
from earth

Figure 9-11.—Fixed direction in space.

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Effect of Mechanical Drift

The line of direction of a gyro is not always in the direction in which it theoretically should point. The direction depends upon its application. In the case of a stable element the axis of spin should be vertical. Looking at it another way, the rotor should spin in a horizontal plane.

A directional error in a gyro is produced by random inaccuracies in the system caused by mechanical drift and the effect of the earth's rotation (apparent drift).

We shall see later on how it is corrected for in the Mk 6 stable element. First, let's consider the causes of mechanical drift.

There are three general sources of mechanical drift:

1. Unbalance. A gyro often becomes dynamically unbalanced when operated at a speed or temperature other than that for which it was designed. Remember that the slower the speed of a gyro the easier it is to precess. The static balance of the gyro may be upset because its center of gravity is not at the intersection of the three major axes. Some unbalance of both types will exist in any gyro since manufacturing processes cannot produce a perfectly balanced gyro.

2. Bearing friction. Friction in the gimbal bearings results in loss of energy and incorrect gimbal positions. Friction in the rotor bearings causes mechanical drift only if the friction is not symmetrical. An even amount of friction all around in a rotor bearing results only in a change of the rate of rotation.

3. Inertia of gimbals. Energy is lost whenever a gimbal rotates because of the inertia of the gimbal. The greater the mass of the gimbal, the greater the drift from this source.

The complete elimination of mechanical drift in gyros appears to be an impossibility. However, by proper design it has been kept to a minimum. Any error which still exists can be corrected for. You may be wondering why an FT cares about design. The reason for listing some of the sources of drift was to impress upon you that a gyro does have sources of error built into it. Furthermore, when you work on a gyro don't unintentionally increase these errors. An easy way to do this would be to allow dirt, a piece of solder, or other foreign matter to get into a gimbal bearing. Excessive lubrication is another source of error.

Keeping the Gyro Vertical

The simple 2-degree-of-freedom gyroscope such as you studied in a previous section would, if set with its spinning axis vertical to the earth's surface and parallel to the direction of gravity, become a direction-indicating device. Once set, it would continue to point in the vertical as long as no disturbing forces caused it to precess from this position. Given time it will precess from the vertical. The disturbing forces or torque caused by apparent and mechanical drift are always present. To find and maintain a vertical position, or any other position, a gyro-erection system is necessary.

To make a gyroscope into a direction-indicating device and one which indicates accurately at all times, the following requirements must be met:

1. Torques must be provided of the correct magnitude and direction to precess the gyro in such a manner that the spinning axis is brought to the desired direction after the rotor has been set spinning.

2. Torques must be provided to precess the gyro back to the required position at the proper rate and direction so as to cancel the effects of apparent and mechanical drift.

The torques required to produce the proper precession to convert the gyro into direction-indicating device are provided by an erecting system. Erection may be accomplished pneumatically, mechanically, or electrically, depending on the type of power available, and is usually activated in response to the force of gravity. Specific erection systems are many and varied. We will discuss in detail the system used in the Mk 6 stable element. When used, erection is a continuous process. Remember, once the gyro has been set spinning in the desired direction, erection is necessary only when the time the gyro is in use is long enough for the earth's rotation and mechanical drift to be great enough to have effect.

Go back to figure 9-8A again, and suppose the base of the fork is fastened to the rolling and pitching deck of a destroyer. A roll of the ship tilts the fork, so as to lower the nearest prong. This SHOULD have no effect on the gyro. The gyro case should rotate on the z-z axis, and the gyro should stay vertical. But suppose there is a little FRICTION in the z-z bearings. This will exert a slight DRAG on the gyro case, tending to ROTATE the gyro about the z-z axis causing the gyro to precess AWAY FROM THE VERTICAL, about the y-y axis.

As you already know, one of the purposes of the gyro is to maintain a TRUE VERTICAL on a rolling and pitching ship. This instrument is called a stable element or a stable vertical depending upon its application. However, they have one thing in common—both instruments accurately maintain a true vertical.

The bearings used in these instruments are nearly frictionless, but there is always enough friction to cause trouble. Over a period of time, these slight frictional forces will move the gyro a long way from the vertical.

That means you need some corrective force which will bring the gyro back to the vertical when it wanders away. This force is provided by the gyro ERECTING SYSTEM.

The most common type of erecting system consists of two tanks of mercury, fastened to opposite sides of the gyro case. The two pools of mercury are connected at the bottom by a small tube (fig. 9-12). An air tube connects the tops of the two tanks in order to prevent the formation of a vacuum.

Figure 9-12 is a schematic view of the gyro case with the gyro tilted away from the vertical. Gravity causes the mercury to run from the high tank into the low tank. Therefore the low tank becomes HEAVIER than the high tank. This sets up a force which tries to tip the gyro farther. The gyro RESISTS this force and PRECESSES to one side—tilting the top of the gyro axle toward you.

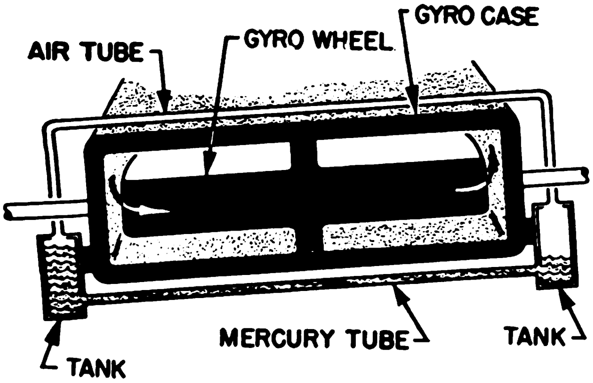

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Figure 9-12.—Mercury system of a stable element.

So far, not much has been accomplished toward getting the gyro back to the vertical. That comes next. Notice that the tube connecting the two tanks is rather small. Therefore the mercury flows slowly. After the case is tilted, it takes nearly a second for the mercury to find its level.

At the same time, the fork is being rotated by a small motor about 18 times a minute. (Figure 9-13 is a schematic diagram of the gimbal rotation system and mercury ballistic system.) Therefore, during the second that it takes for the mercury to flow into the low tank, the fork and the entire gimbal assembly has rotated 90 degrees. As before, the weight of the mercury is trying to tip the gyro sideways, but this time 90° away from the actual tilt. Thus, the gyro precesses back TOWARD THE VERTICAL.

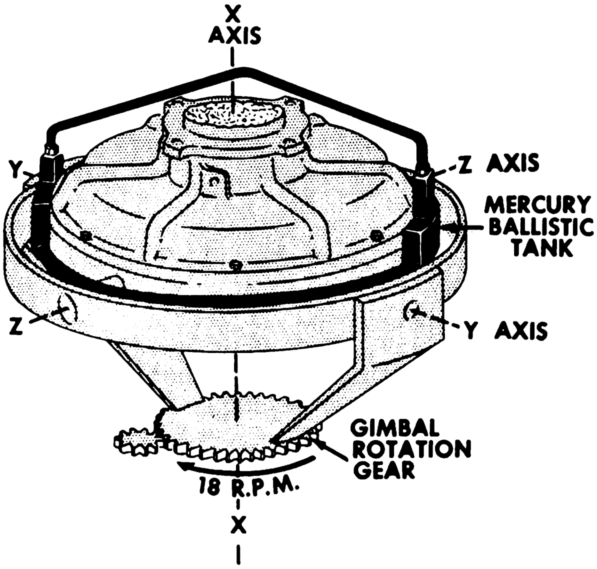

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Figure 9-13.—Gimbal rotation.

You will see this more clearly if you think about what happens during one rotation of the fork. The result is indicated in figure 9-14 in which you are looking straight down at the top of the gyro case and the mercury tanks. Understand that this diagram is purely schematic. It is intended to give you an idea of the principle involved, not a complete picture of what happens to a gyro in actual operation.

Suppose that the gyro spin axis is suddenly tilted toward the north at an instant when the mercury tanks are lined up north and south (fig. 9-14A). Mercury STARTS to flow into the north tank, but at first no precession occurs because of the lag or time delay in the mercury flow.

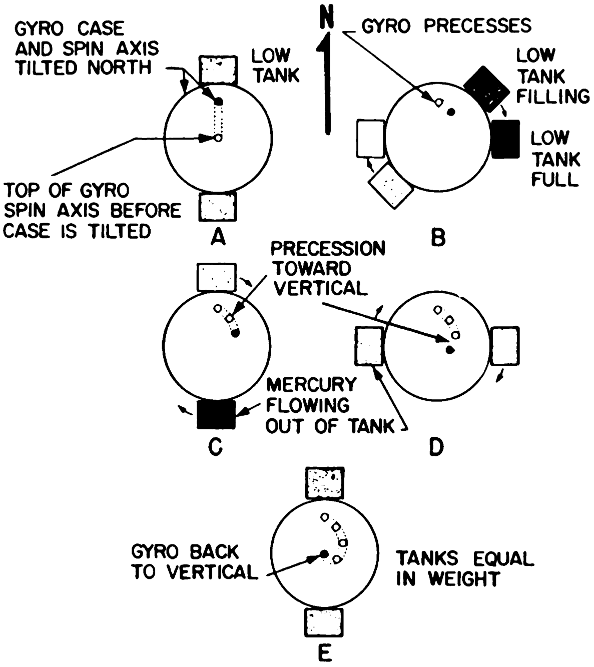
As the case rotates, the low tank is moving toward the east and is filling up with mercury. As the lower tank fills, the gyro begins to precess faster and faster in a generally southeasterly direction. By the time the low tank is FULL, it is headed east (fig. 9-14B) and the gyro is precessing rapidly south.

Continued rotation puts the loaded tank on the high side, and the mercury begins to flow out of it (fig. 9-14C). But the tank is still heavy, and therefore the gyro precesses generally southwest (fig. 9-14D). By the time the tanks are again lined up north and south, the mercury in the two tanks has equalized (fig. 9-14E). The second tank is now the low tank. It begins to fill up, and the entire process repeats.

You can see that the easterly and westerly precessions tend to cancel. The net effect is a precession toward the south, bringing the gyro BACK TO THE VERTICAL.

Thus, you can see that whenever the gyro is started, the mercury system will bring it quickly to the vertical. And at any time the gyro wanders off the vertical, the mercury system will bring it back.

Ask one of the Fire Control Technicians in your division to start the stable element or stable vertical on your ship so you may watch the GIMBAL-ERECTING SYSTEM in action. You'll notice that at first the gyro will precess rapidly towards the vertical. But you'll also notice that the erecting system may require as much as 10 minutes to correct the last few minutes of error. This is because as the gyro comes nearer to the true vertical, less mercury flows from one tank to the other during a rotation of the gimbals. Consequently the precessional force is small and the rate of precession is very slow. In some gyro systems—the master gyro compass, for example—it may take as long as 24 hours for the gyro to finally settle down in its true position.


GYRO CASE AND SPIN AXIS TILTED NORTH
LOW TANK
TOP OF GYRO SPIN AXIS BEFORE CASE IS TILTED
A
N
GYRO PRECESSES
LOW TANK FILLING
LOW TANK FULL
B
PRECESSION TOWARD VERTICAL
MERCURY FLOWING OUT OF TANK
C
D
GYRO BACK TO VERTICAL
TANKS EQUAL IN WEIGHT
E

12.147

Figure 9-14.—Effect of rotating the fork.

Let's review the main purposes of the gimbal-erecting system of a stable element or stable vertical. First of all, it brings the gyro to the true vertical when the gyro is started. Second it compensates for the effect of friction and other irregularities in the gimbals which could cause the gyro to precess away from the vertical.

There are several other types of erecting systems used with gyros. You will learn these in later fire control manuals. If you are in doubt about the mercury system, go back over the text, for it is the basic erecting system of modern fire control gyro stabilizers.

Latitude Correction

A few pages back we mentioned that there are two kinds of action which tend to pull a gyro out of the vertical. One of these is the random effect of bearing friction and other similar irregularities. You have seen how a mercury erecting system overcomes this effect.

In addition to these random actions, the ROTATION OF THE EARTH has a continuous effect on the gyro. Remember that gyroscopic stability (also called rigidity of plane) means that a gyro axle tries to maintain a fixed direction IN SPACE. But the earth, as it rotates toward the east, is rolling under the gyro. Therefore, to an observer standing on the earth, the gyro appears to keep tipping westward. Apparent rotation was described in an earlier article and effect was observed from a position over the South Pole. Let's reverse our position and look at the effect of the earth's rotation.

This effect appears clearly in figure 9-15. The figure is a view of the earth as it would appear if you were looking down on the North Pole. Image that a gyroscope has been erected on the Equator at Point A with its axis vertical (Perpendicular to the surface of the earth), and that because the gyroscope has frictionless bearings and no erecting system you must rely on gyroscopic stability to keep it vertical. After a few hours, the rotation of the earth will move point A to the position marked B.

The gyro still heads in the same direction in SPACE, but it is no longer VERTICAL. Its axis is no longer perpendicular to the earth's surface at that point. To anyone standing on the earth, it appears to be leaning to the west. After 6 hours, when the earth has made a quarter turn,

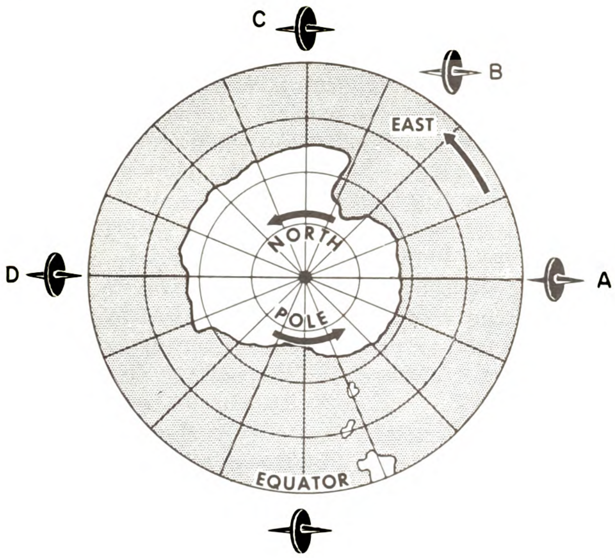


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Figure 9-15.—Apparent rotation at the equator.

the gyro will be horizontal, as at C. After 12 hours (at position D) it will have turned completely over and will be upside down. And after 24 hours, the gyro will have made a complete revolution.

In other words, the gyro is tilting WESTWARD at a rate of 15° per hour.

The mercury-erecting system of the stable element won't quite prevent all of this tilt. The gyro, therefore, must be made to precess EASTWARD at 15° per hour.

Now when the gyro is truly vertical, the mercury system causes no precession. The mercury affects the gyro only when the gyro is tilted. And so, if we were to rely on the mercury system to produce the required eastward precession, the gyro would always lean slightly to the west. It would NEVER be truly vertical, as it should be for efficient fire control. An error would always persist, being maximum at the Equator, and gradually decreasing to zero at either pole.

When a gyro is vertical, therefore, you correct for the effect of the earth's rotation at all times by applying to the gyro some force that will cause a steady eastward precession. This means that in dealing with Navy stable elements or stable verticals the top of the gyro axle must be pushed northward.

This can be done by extending a small arm northward from the top of the axle, and by handing a weight on the north end of the arm as in figure 9-16. The weight will keep trying to tip the axle northward, and this will cause an eastward precession.

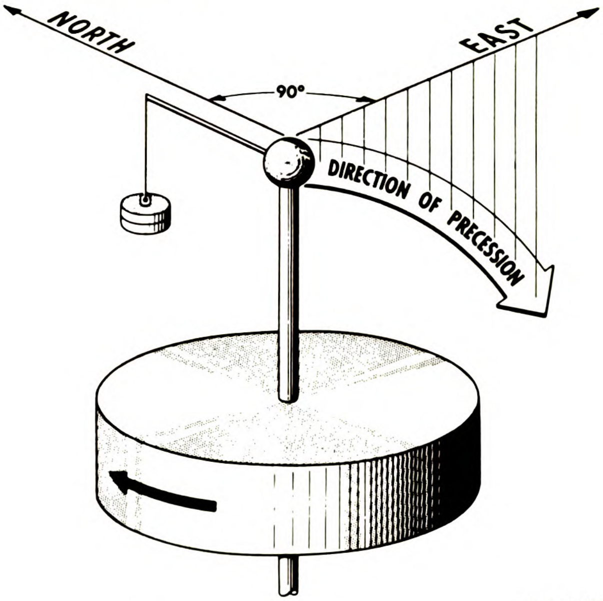

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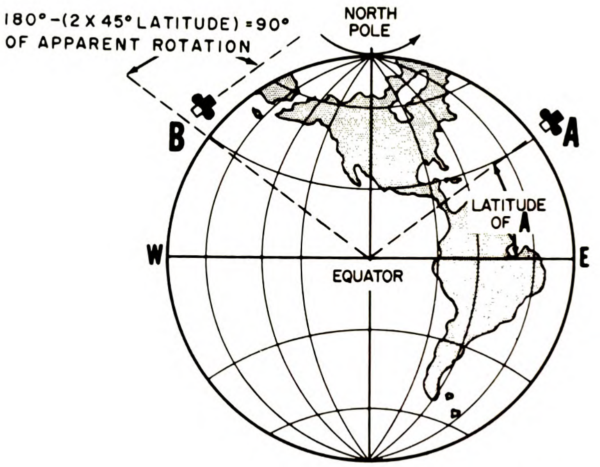
Figure 9-16.—Latitude correction weight.

Up to now, it's been assumed that the gyro is located at the Equator. A little thought will show you that if the gyro were placed at the North or South Pole, the rotation of the earth would have no tendency to move it out of the vertical. The gyro's axis is parallel to the earth's axis. Apparent rotation is about the gyro's spin axis and no effect will be observed. So you would expect that at points on the earth between the Equator and the Pole, the gyro would tilt westward at a speed LESS than 15° per hour. This is true, and figure 9-17 shows you why. If a gyro is set vertical at A, it will move to point B in 12 hours, and will tilt through an angle of 180° minus 2 x latitude of A (instead of through 180° as it would be at the Equator).

This means that the precessional force should be decreased in higher latitudes. You can slow down the precession by moving the compensating weight inward on the arm, closer to the gyro axle. The arm has markings on it to show you the correct position of the weight for any latitude (fig. 9-18). The weight is called the LATITUDE-CORRECTION WEIGHT.

Figure 9-18 shows the appearance of the gyroscope and its case. Notice, in the cutaway portion, that the GYRO WHEEL is the rotor of a 3-phase a-c induction motor. The case forms



12.150

Figure 9-17.—Effect of earth's rotation at mid-latitudes.

the motor stator. This gyro-driving motor is operated by 70-volt 146-cycle ac obtained from a special MOTOR GENERATOR set. The 146-cycle current is used in order to permit high gyro speeds. The maximum speed which can be obtained from 60-cycle current with an induction motor is only 3,600 rpm, but 146 cycles permits nearly 146 times 60, or 8,760 rpm.

In later training manuals you will learn more about how the gyro is used in the stable element and stable vertical. These manuals will explain how the stable element measures the amount of roll and pitch of the ship, and how it manufactures the correction angles for the computer.

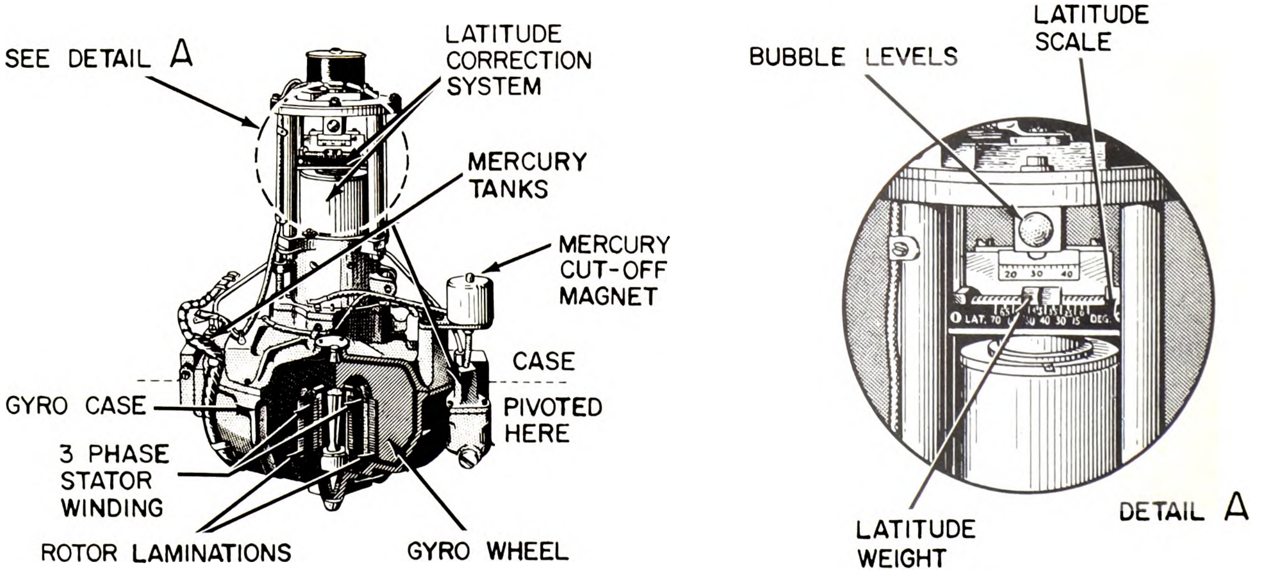
Different systems use different types of erecting systems. However, the mercury gimbal-erecting system is the most common. You will learn other types later in your fire control career. But no matter what type of gyro-erecting system you encounter, its basic purpose will be the same. It helps the gyro to find and maintain a vertical position, which is used to correct gun orders for the rolling and pitching of the ship.

If you learn the basic gyro theory, the rest is easy. No matter how the gyro is used, it will always display the same familiar characteristics—RIGIDITY OF PLANE OF ROTATION. AND PRECESSION.

The free gyro in the stable element maintains its spin axis vertical with respect to the earth, and not space. Gravity acting on the erecting system causes the gyro to precess so that the spin axis is always in the vertical plane. In other words, the gyro tracks the local vertical by using its property of precession.

SINGLE-DEGREE-OF-FREEDOM GYROS

When we covered the degrees-of-freedom found in gyros we briefly discussed one use of a single-degree-of-freedom gyro. This type of



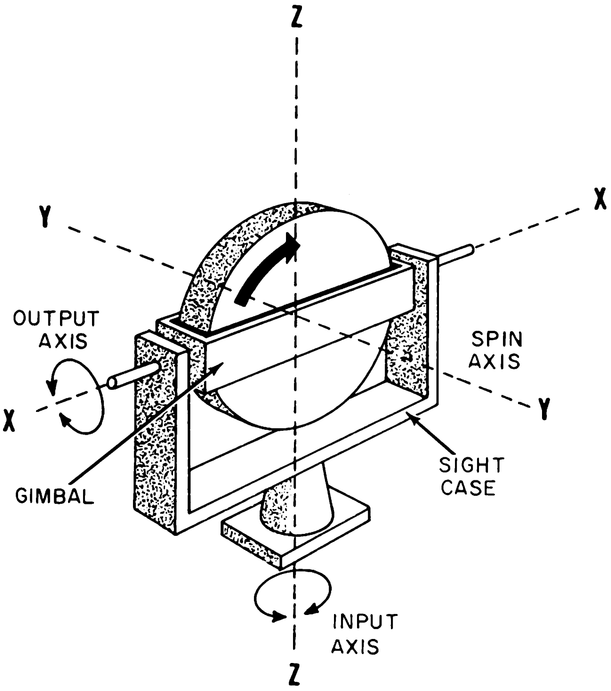
12.151

Figure 9-18.—Gyro case of the stable element.

gyro is used extensively in fire control equipment as both a computing device and a stabilizing device. To see how it performs these functions let's first look at its construction.

A gyro wheel is mounted in a gimbal and spins in the y-y axis, (fig. 9-19). When the wheel is spinning it has rigidity in the y-y spin axis and will resist an attempt to change its plane of rotation. The gimbal is supported in the two arms of the mounting frame, and can pivot about the X-X output axis. The X-X axis is the only one in which the gyro can precess. In all other directions there is a fixed mechanical coupling between the gyro and its mounting. The mounting frame can be rotated about the Z-Z axis.

An angular motion about the Z-Z input axis will tend to change the gyro's plane of rotation. Therefore, if you rotate the gyro mounting about the Z-Z axis, the gyro will precess as shown in figure 9-20. Offhand, the gyro does not appear to be obeying the laws of precession. But stop to consider this: rotating the gyro case is the same as applying a force on the spin axis. Hence the direction of procession shown is correct. You can check it with the right-hand rule. A study of the figure will show that the gyro is sensitive only to angular motion about the Z-Z axis.



12.152.1
Figure 9-19.—Single degree-of-freedom gyro.

It is important to remember that the rate of precession is directly proportional to the precessional force, and inversely proportional to the resistance of the gyro to that force.

Since the rate of precession is proportional to the applied force, you can increase the rate of precession by increasing the speed with which you rotate the gyro mounting. In other words, gyro precession is a result of an angular velocity about the input axis. The amount of gyro precession is determined by the strength of the precessional force, the time the force is acting, and the gyro's resistance to the force.

Initially, the gyro establishes a reference plane aligned with the center of the support arms. The gyro's displacement from the reference plane is equal to the product of the angular velocity (force) and the time the force is acting on the gyro. This last statement is somewhat familiar for mathematically a displacement is equal to the product of velocity and time. Since a single-degree-of-freedom gyro can detect and measure an angular rate of change of position of an object, it is capable of mechanically solving this type of problem.

Now let's look at some of the applications of single-degree-of-freedom gyros in fire control equipment. In fire control we are primarily concerned with the angular rate of change of a target's position. The director/radar tracks a target, measuring the target's position and changes in its position. Gyros are used to measure the angular rate of the line of sight, and hence of the target. Tracking errors are introduced into the gyro system as a rate error or as a displacement error. The type of error is determined by the tracking method. Normally, where the gyro has a rate input the fire control computer solves for the tracking rate. The computed rate is compared with the rate of movement of the director as measured by the gyro.

A displacement error to the gyro normally originates in the radar or optical tracking system. The displacement error is equal to the linear distance between the target's present position and the line of sight. The displacement error to the gyro varies the angular rate of the director. But before we get ahead of ourselves, in the theoretical side of the discussion, let's go to some examples of actual applications, and leave the mathematical theory to a later course. We will start with a rate-of-turn, or rate gyro.

RATE GYROS

Rate gyros found in fire control equipment may be called by different names, depending on what OP or other reference you are reading. Nevertheless, no matter what name is applied to a gyro which measures rate of change it can be called a rate gyro.

Like the free and vertical gyro, the rate instrument contains a mechanical system consisting of the spinning rotor and associated gimbal system. It differes in that it has one gimbal, so that one degree of freedom is obtained. Further, the rotor is restrained by some means, usually a spring, when it is precessed.

RATE-OF-TURN GYRO

A good example of a rate gyro is the type used in a lead-computing sight. The sight uses a pair of rate-of-turn gyros. A rate-of-turn gyro is installed to take advantage of the property of precession. This precession is carefully measured in terms of bearing and elevation target tracking rates. These rates, after certain modifications become gun elevation and gun train orders.

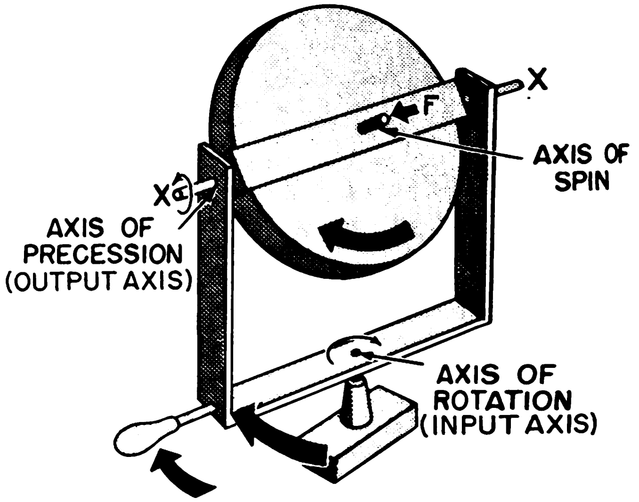
That is a pretty broad statement, so let's look at a typical problem of a lead computing sight. There is nothing like a good concrete example to explain why gyros are used to calculate the lead angles of high speed targets.

Consider the case of a high speed jet fighter sweeping by your ship at a 1000 yard range. His bearing rate would be so fast that a mechanical computer would not have time to arrive at a solution.

But the fact remains that these targets are dangerous and have to be knocked down. This means that some type of computing mecanism must be used; a type which is still faster than the ones using the mechanical components you have studied in previous chapters. And the GYRO is the answer.

You know that a force applied at F will cause the gyro to precess at right angles to the force, (fig. 9-20). Likewise, attempting to turn the gyro case will cause the same result. The gyro will precess as shown by the arrows, around the x-x axis.

Since the rate of precession is proportional to the applied force, you can increase the rate of precession by increasing the speed with which you are moving the gyro case (fig. 9-21). In other words, you have a RATE-OF-TURN GYRO.


X
F
AXIS OF SPIN
X
AXIS OF PRECESSION (OUTPUT AXIS)
AXIS OF ROTATION (INPUT AXIS)

12.152.2
Figure 9-20.—Gyro precession.

The FASTER you turn the gyro case, the MORE the GYRO will PRECESS, for the amount of precession is proportional to the rate of turn.

This characteristic of a gyro, when properly controlled, fits the requirements of a high-speed lead-computing sight. Let's see what is necessary to control the gyro properly.

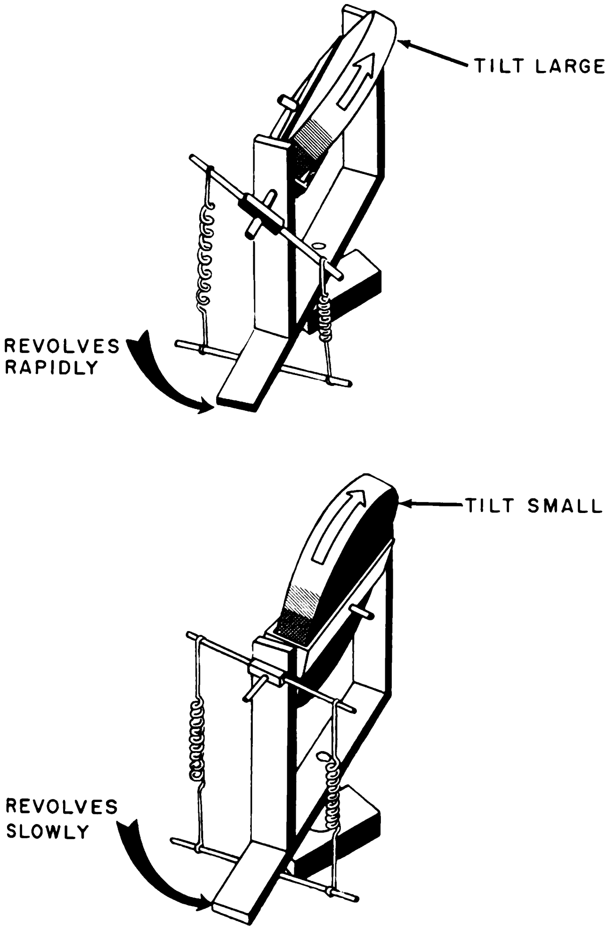
In figure 9-22 is shown the method of restraining (controlling) the precession of a gyro to permit the calculation of a lead angle. A pair of SPRINGS have been attached to the crossarm on the x-x shaft. These springs serve to restrain the FREE precession of the gyro. The gyro is harnessed to produce some useful work.

As a gyro precesses, it exerts a force which is proportional to the momentum of the spinning wheel and the applied force.

For example, suppose you rotate the gyro case at a speed which is proportional to applying a horizontal force of 2 pounds at F. Obviously, the gyro will precess; and as it does, it will cause the crossarm to pull up on spring A with a CERTAIN FORCE—say 1 pound. (This would vary with the length of the crossarm.)

If you CONTINUE to turn the gyro case at this rate, the precession of the gyro will continually exert a pull on the spring. More precisely, the gyro will precess until the 1-pound pull of the crossarm is exactly counterbalanced by the tension of the spring.

The gyro will continually try to precess farther, but since its pull is balanced by the tension of the spring, it will remain in a fixed position



12.152.3

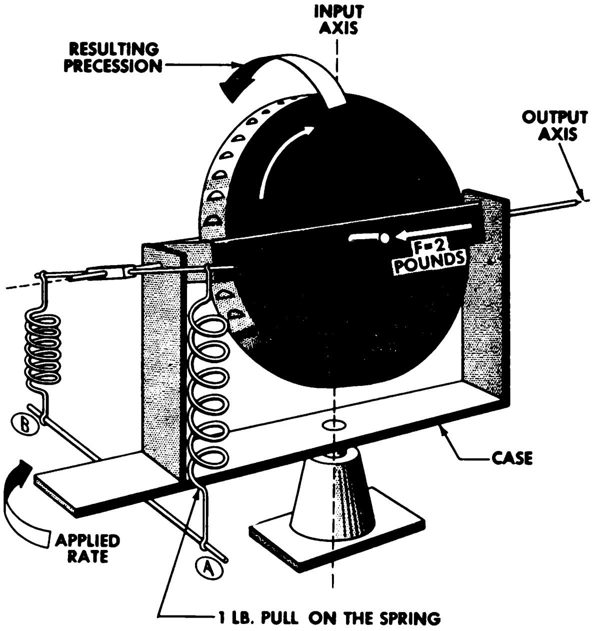
Figure 9-21.—Precession is proportional to the rate-of-turn.

as shown in figure 9-22. That is, it will REMAIN in the PRECESSED POSITION as long as you CONTINUE TO ROTATE THE CASE AT THE SAME CONSTANT SPEED.

When you stop moving the gyro case, it is equivalent to removing the force at F, and the gyro stops precessing. The spring is still exerting a pull, however, so it pulls the crossarm back to the horizontal.

Suppose you rotated the case twice as fast as before. That would be equal to a 4-pound force at F and a resulting 2-pound pull by the cross-arm on spring A. So the gyro would precess twice as far, before the tension on the restraining spring equalled the pull of the cross-arm.

Boiling it down, the faster you rotate the gyro case the father the gyro will precess before the pulls of the crossarm and spring are equal, and the gyro comes to rest.



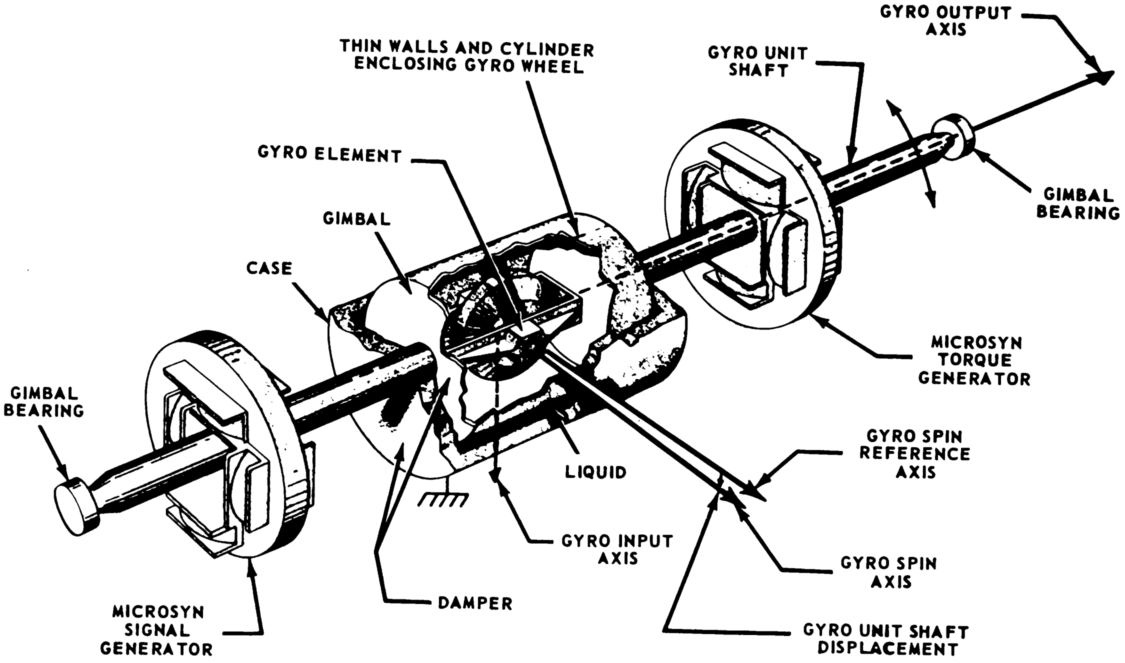
12.153

Figure 9-22.—Precession of a spring restrained rate-of-turn (rate) gyro.

Outside of a few refinements, such as an optical and mechanical linkage system, that's all there is to a simple lead-computing sight. The gyro shown in figure 9-22 is mounted in a case which can be turned by handlebars. Then as you train the case to follow a fast-moving target the gyro precesses, generating a lead angle. In the chapter on the Mk 63 gun fire control system you will learn more of how gyros are used in a sight. You will learn that the tension on the restraining springs is calibrated according to range to the target. You will also learn that the precession of the gyros moves a system of linkages and mirrors, causing an illuminated reticle to be displaced by the correct lead angle.

FLOATED GYRO UNIT

Another type of gyro widely used in fire control equipment is the floated gyro unit. This unit, also called the draper gyro and hermetically sealed integrating gyro (HIG), to list a few of its more common names, is a viscous damped, single-degree-of-freedom gyro with a torque generator and a signal generator mounted on its output shaft. Figure 9-23 shows a cutaway view of the unit. The principal components of the



12.154

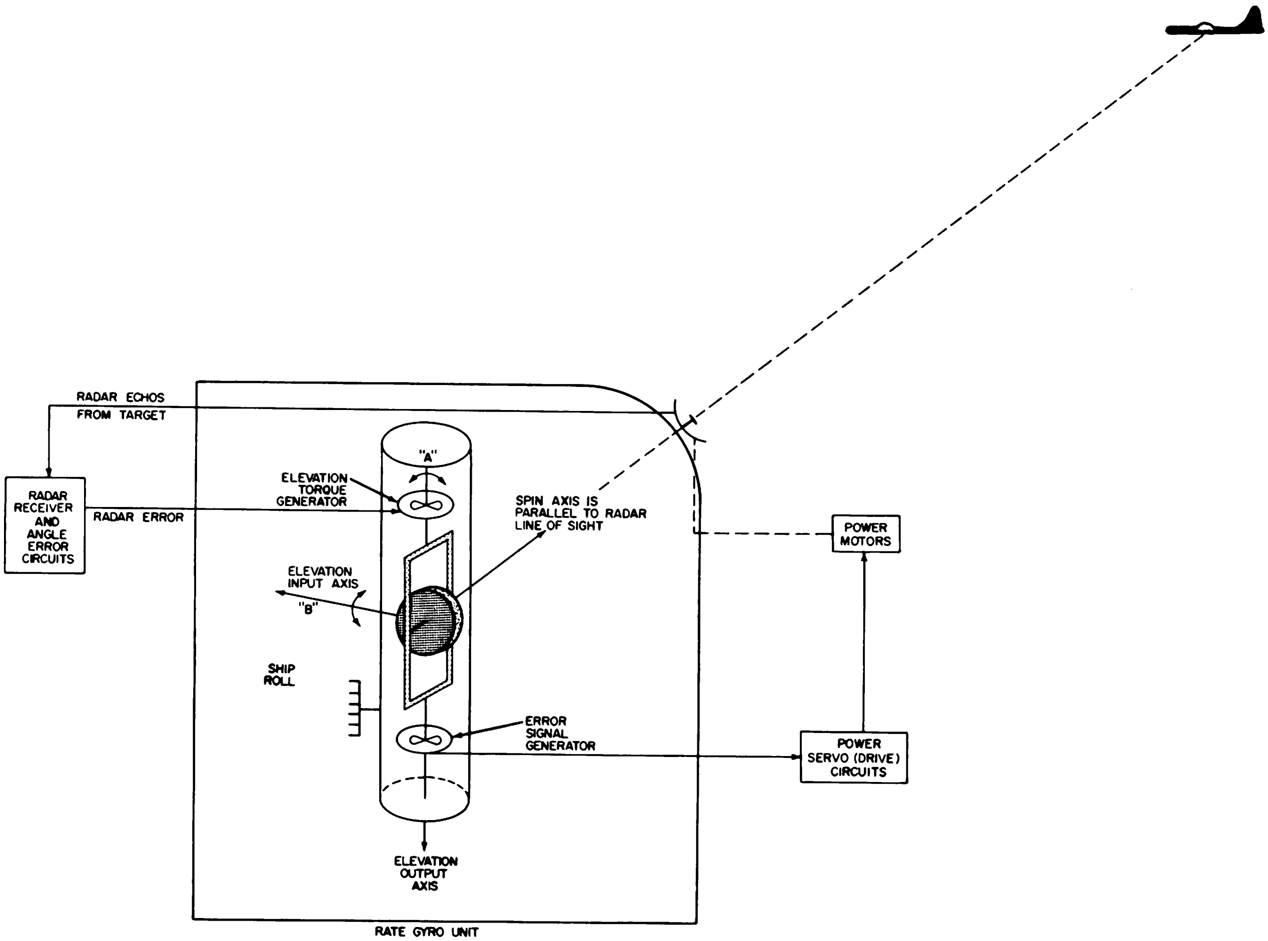
Figure 9-23.—Floated gyro unit.

gyro are the gyro rotor, gimbal, signal generator, torque generator, and the viscous damping fluid. The gyro rotor and stator are in a sealed cylinder filled with a gas, usually helium. The gas serves to transfer heat generated by the gyro stator windings to the surface of the cylinder. The closed metal cylinder acts as the inner gimbal and is mounted on precision bearings. The space between the gimbal and case is filled with a viscous damping fluid of high specific gravity. Because of the high specific gravity of the fluid it serves to float the inner gimbal and its shaft. This reduces the gimbal bearing friction. In this way mechanical drift due to friction is greatly reduced.

The "pick off" is a signal generator whose rotor is attached to one end of the inner gimbal shaft. (The term "pick off" is the name usually used for that part of a gyroscopic unit whose function is to change the output of the device into a usable signal.) The electrical output of the signal generator is proportional to the angular displacement between the inner gimbal and the case. The torque generator, the rotor of which is attached to the other end of the inner gimbal shaft, provides a means of applying command signals to the gyro to cause it to precess.

A typical fire control application of a floated gyro unit is in the automatic radar tracking (angle servo) circuits of fire control directors or radar sets. Before discussing the action of the floated gyro unit, it is necessary to consider first the overall operation of the entire tracking system. We will divide it into convenient groups of units and indicate the general function of each unit, so that their operation may be understood in relation to the operation of the system as a whole. The complete system is used for tracking targets automatically, and for stabilizing the line of sight in the presence of ship motion. It may be considered as consisting of six major units: the radar receiver, the angle error circuits, the rate gyro unit, power drive servo circuits, power motor, and the radar antenna.

Operating together, these groups of equipments function as a large servomechanism to position the radar antenna. Conception of the radar automatic tracking loop as a servomechanism can be represented by means of a generalized block diagram as in figure 9-24. The figure refers to no particular system. It indicates the basic types of components, and antenna control methods usually employed in the elevation tracking circuits of missile and gun fire control systems.


RADAR ECHOS
FROM TARGET
RADAR RECEIVER AND ANGLE ERROR CIRCUITS
RADAR ERROR
ELEVATION TORQUE GENERATOR
"A"
SPIN AXIS IS PARALLEL TO RADAR LINE OF SIGHT
POWER MOTORS
ELEVATION INPUT AXIS
"B"
SHIP ROLL
ERROR SIGNAL GENERATOR
POWER SERVO (DRIVE) CIRCUITS
ELEVATION OUTPUT AXIS
RATE GYRO UNIT

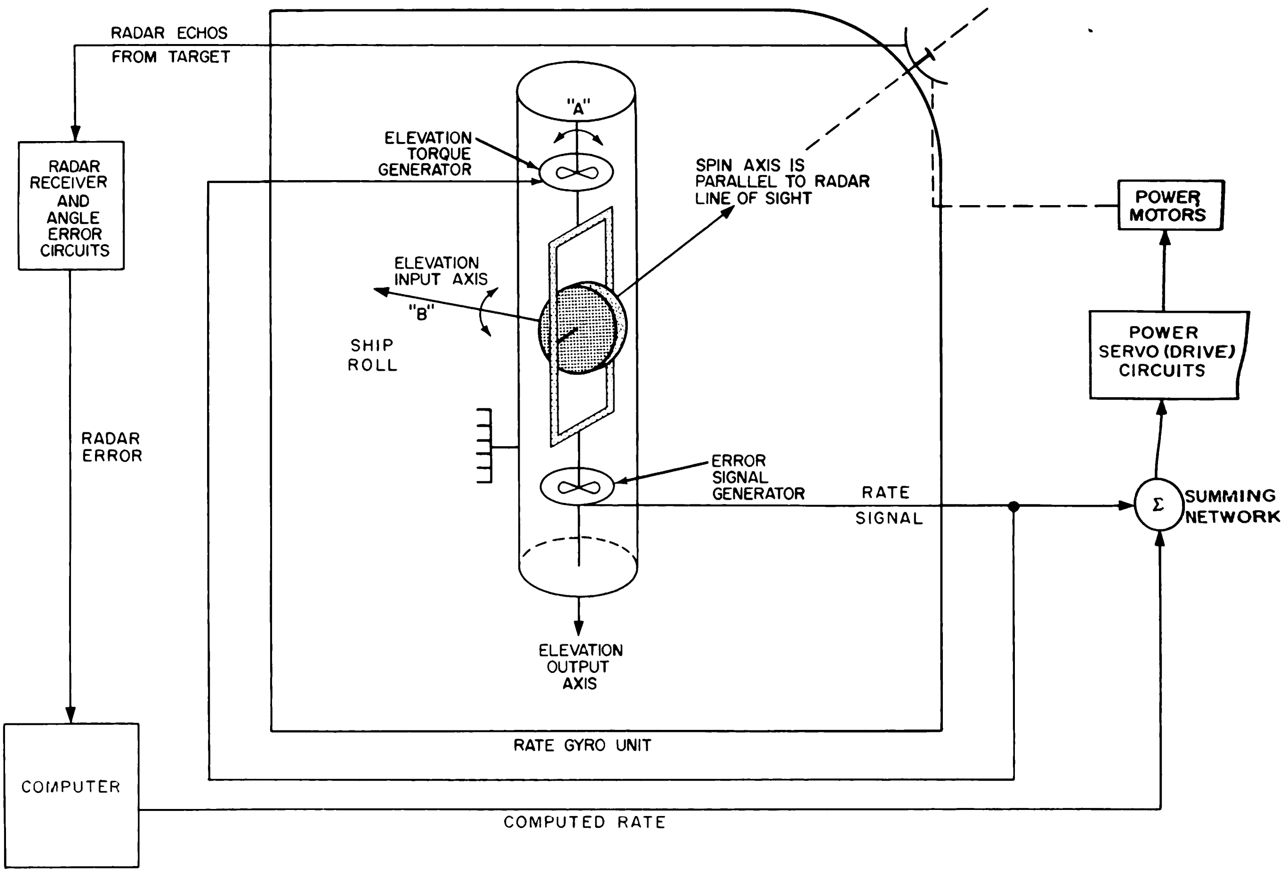
12.155.1

Figure 9-24.—Simplified block diagram of an automatic tracking system.

The following describes what takes place in the system in case of an elevation radar error signal and ship's motion. Operation is essentially the same for traverse. The radar receives target echoes from the antenna and converts them into radar error signals. These signals indicate how far and in what direction the radar beam is off target. They are applied to the gyro unit torque generator to cause the gyro to precess so that its spin axis swings in the direction in which the radar beam should move to follow the target. Appropriate error signals are produced by the signal generator and sent to the antenna power drives to cause the radar beam to align itself with the gyro spin axis. In this manner the radar beam continuously tracks a target. This method of control illustrates how the principle of gyroscopic precession is used. The fundamental principle of rigidity of a gyro can also be shown.

Assume for the moment that the radar antenna is not tracking a garget. This produces no radar error signal. The ship starts to roll and pitch. A torque is produced about the input axis of the gyro in the gyro unit, precessing the gyro and turning the output shaft. Error signals are generated by the signal generators proportional to the rate of change of ship motion. These signals are amplified and sent to the power drives to position the antenna. Movement of the antenna causes the gyros to precess to their original position. This action has the effect of making the radar line of sight remain fixed in space while the ship rolls and pitches beneath it.

Now that you have an overall picture of how the elevation automatic radar tracking circuit



12.155.2

Figure 9-25.—Simplified block diagram of an automatic tracking system with rate signals.

works, let's take a closer look at the rate gyro unit. Figure 9-24 shows a simplified block diagram of it. The elevation radar error signal is applied to the torque generator, producing a torque "A" about the gyro output axis. At the same time, any torque caused by ship roll or pitch that may be present about the input axis will cause the gyro to precess. This torque is marked "B" in the figure, and it produces another torque about the output axis. Torques "A' and "B" are algebraically added about the output axis. The resultant torque or twisting effect is opposed by the viscous fluid. Since the viscous fluid has integrating properties, the signal generator rotor will be turned through an angle which is the integral of the resultant torque. In other words, the output of the signal generator depends upon the total torque causing precession and the duration of precession. The output of the signal generator drives the elevation power servo to move the antenna. Movement of the antenna cancels the radar error signal, and removes the signal to the torque generator. As the antenna moves in elevation, the elevation gyro is precessed in a direction to zero the output of the signal generator.

A second method of using this type gyro in a director drive is with a rate input to the torque generator. In figure 9-25 the fire control computer solves for the angular tracking rate. The computed rate is transmitted to the director drive to control its angular velocity. The angular motion of the director will cause gyro precession. The gyro signal generator's output is proportional to the angular velocity of the director. The gyro velocity signal is added to the computed velocity signal in the summing network. The sum of the two is the input signal to the power drive.

At the same time the gyro signal is fed back to the gyro torque motor. The motor will apply a torque to the gyro to tilt it back toward its neutral reference plane. Therefore the gyro is delicately balanced between the precessional force "B" caused by the director rotation and the feedback torque "A", which is a measure of the present angular velocity of the director. Any change in the director's angular velocity will change torque "B", which will disturb the gyro balance and cause it to precess. The output of the gyro signal generator will therefore be proportional to the rate of change of velocity, or an acceleration signal.

CAGING.—Caging is the act of holding a gyro so that it cannot precess or change its attitude with respect to the body that contains it. It is done for two reasons. First, by caging a gyro prior to the application of power the initial reference attitude is attained. Free gyros are frequently used in missiles to provide a space reference. The free gyro is caged prior to launch in the desired attitude and then uncaged at the time the missile is launched.

Second, gyros are caged as a protective measure or to prevent unwanted precession. During the designation and acquisition of targets a director is subjected to violent motion. This produces torques which could cause the director's gyros to tumble. If allowed to happen, this will result in bearing damage, and may possibly cause the rotor to jump out of its gimbals. Tumbling is prevented by caging the gyros during the designation and acquisition modes of director operation. In lead-computing sights the gyros are caged while slewing the director on target to prevent generating false lead angles.

Gyros are also caged during shipment and storage to prevent possible bearing damage due to handling shocks.

Caging can be accomplished by driving a pin into one of the gimbals, either electrically or pneumatically. It may then be uncaged at the desired time by pulling the pin.

CHAPTER 10

LEAD-COMPUTING SIGHTS AND GUN FIRE CONTROL SYSTEM MK 63

INTRODUCTION

Increased aircraft speeds have made necessary the development of fire control systems which can further reduce the time required for solution of the antiaircraft problem. The Navy has developed a zone system of defense. The first zone consists of fighter planes, called the Combat Air Patrol (CAP). The second zone consists of the ship's antiaircraft weapons. CAP should not enter this zone. If a number of aircraft attack simultaneously, some would probably penetrate these zones.

In order to increase the coverage in the ship's weapons zone, the Navy has approached the problem at both long and short ranges. Missile weapon systems have been developed that can detect, track, and destroy targets at extremely long ranges.

Refinements have been incorporated into the fire control systems and the weapons to increase their overall accuracy. This increases the probability of target destruction; but the increased range and the refinements have also increased the size of the weapon system. Hence the number of long-range systems which can be installed on a ship is limited. Moreover, longer ranges have increased the "busy" time for each system per target destruction. Consequently, the long range systems cannot provide the kind of divided fire that is mandatory for an adequate defense against a multiple target attack.

A family of lead-computing, relative-rate systems for defense against high sped targets at intermediate and short ranges have been developed. These systems are capable of tracking targets with very high relative angular rates, and can automatically and almost instantaneously compute the gun corrections necessary to ensure a hit. In chapter 2 of this course we covered the fire control problem and found that the ballistic corrections for gravity, drift, wind, and initial velocity will increase as range increases. Since the system discussed in this chapter deals with relatively short ranges, the computing devices will not have to be as refined as in the long-range systems. Hence the short-range systems are light in weight and small in size. Thus a control system can be installed for each gun mount to furnish maximum controlled coverage of targets.

The short-range problem has to deal with high angular rates in train and elevation. These rates are indirectly proportional to range because as range decreases, the angular rates increase. This can be seen by watching a plane on the horizon and one closer to you or passing overhead. For a definite linear distance of the plane's movement, the amount you must move your head or eyes in order to keep the plane in sight depends on the plane's distance from you. The angular rate is the rate at which you turn your head or eyes. This factor, plus the short amount of time allowable for acceptable solution, places severe limitations on any short-range or intermediate-range system.

To overcome the limitations of the system it was necessary to devise a mechanism that could get right to the heart of the problem—one that could measure the angular rates and incorporate the ballistic corrections directly, and come up with an almost instantaneous solution. The characteristics of a gyro, when it is properly controlled, fit these requirements Remember the characteristics of a rate-of-turn gyro: it has only one degree of freedom, and the amount of precession is proportional to the rate of turn (externally applied force). This was covered in chapter 9 of this course.

The rate-of-turn gyro was developed by Dr. C. S. Draper while he was working on a bank-and-turn indicator for naval aircraft. When Dr. Draper became interested in the antiaircraft problems, he was quick to recognize the potential of the rate gyro. He realized that the lead required to hit a target depends on the angular rate of the target, and that this can be measured by a rate gyro. A lead-computing gunsight could be based on the gyro's property of keeping a fixed direction in space except in response to a force applied to its spin axis, in which case the gyro precesses by an amount proportional to the applied force, and in a direction perpendicular to that force.

This means that when a sighting element is controlled in direction by a gyro and pointed at a target, the force required to keep it on the target is a measure of target angular motion. Movement of the gyro in the plane of precession is restrained by variable spring tension. The tension adjustment is calibrated to represent the time of flight of the projectile. The gyrp's precession is applied through linkages to mirrors in the sighting system and displaces the line of sight by the required lead angle. The operator sees a reticle superimposed on the target. By keeping it on the target, he can automatically keep the gun barrel pointed ahead of the target far enough to compensate for relative motion between own ship and target, during the projectile's time of flight. By the addition of simple devices we can compensate for wind, gravity, drift, and changes in initial velocity. The only inputs required are range, range rate, wind, and initial velocity.

THE ANGULAR RATE ANTIAIRCRAFT PROBLEM

In order to properly understand the functions of a fire control system and its component parts, it is first necessary to understand the mathematical principles involved. Before you can understand the HOW of an instrument's functional operation, you must know the WHAT of it, and, for a complete understand, the WHY of it.

The solution of the problem can be divided into three parts, all of which are handled simultaneously in the lead-computing sight.

1. Target motion lead angle
2. Ballistic correction
3. Gun order

The target motion problem involves the determination of the angle through which the target will move during the flight of the projectile. The ballistic problem involves the computation of the angular correction to compensate for the factors affecting the flight of the projectile. These two, the target motion lead angle and the ballistic angle, make up prediction angle. Prediction angle is the total angle of lead necessary to ensure a hit on the target. The gun-order problem involves combining the lead angles with the angles defining the present position of the target at the instant of firing.

TARGET MOTION PROBLEM

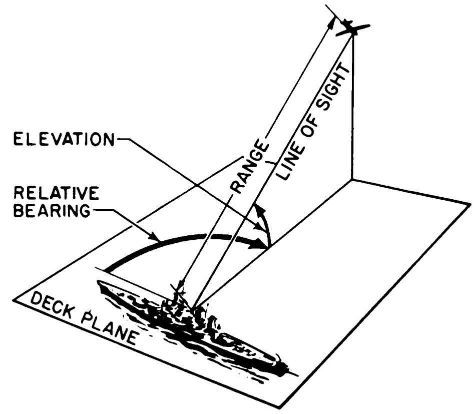
Before a prediction can be made, the position of the target relative to own ship at the instant of firing must be determined. Target's position relative to own ship is defined in three coordinates (fig. 10-1).

1. Relative bearing of the target (measured) in the deck plane, clockwise from the bow of the ship to the plane perpendicular to the deck through the line of sight).
2. Elevation of the target above the deck plane (measured in the plane perpendicular to the deck).
3. Range of the target (measured along the line of sight).

The bearing and elevation coordinates of the target are determined by keeping the target within the reticle of the sight. The range coordinate is obtained from radar or some other source.

Target Motion Lead Angles

To hit a moving target, it is necessary to lead the target—that is, to fire at a point ahead of it. The angles between the present position of the target and the position it will occupy at



12.215

Figure 10-1.—Present target position.

the end of the projectile flight are the target motion lead angles. The lead angles are based on the assumption that the target is flying a straight-line course at constant speed. This assumption is necessary since we have no control over the projectile once it is fired; and it is valid because the target cannot deviate greatly from the straight-line course during the time of flight.

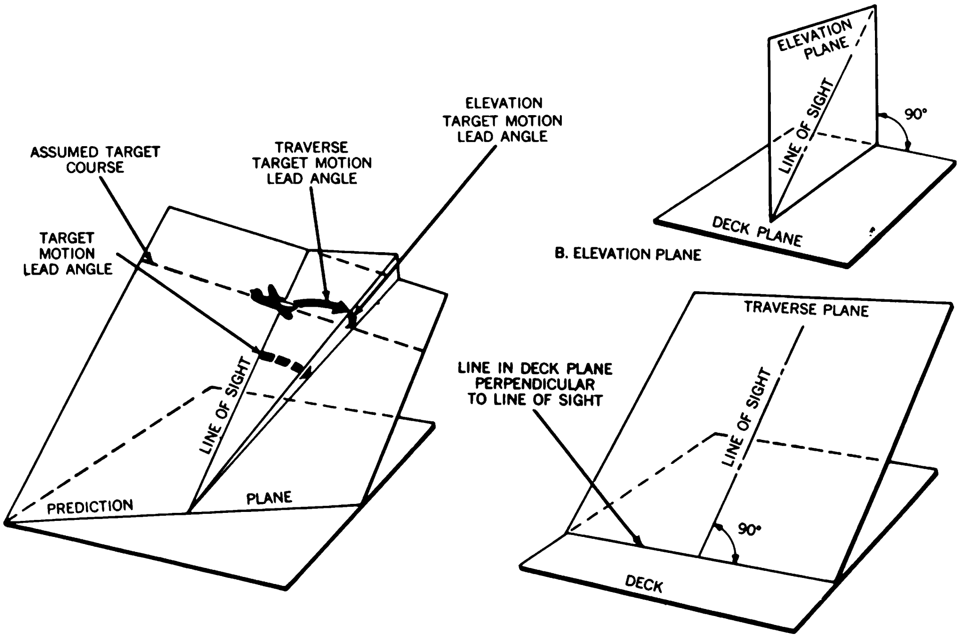
The magnitude of the target motion lead angles depends on the angular rate of the target and on the time of flight of the projectile. The angle rates are measured with respect to the director by the rate-of-turn gyros of the lead-computing sight. The director moves in two planes: train and elevation. Target motion is in a plane called the prediction plane, (fig. 10-2A). This plane contains the line of sight (LOS) and an assumed target course line. Target's motion must be resolved into components in the elevation and train planes of the director.

The elevation plane (fig. 10-2B) is the plane through the LOS and perpendicular to the deck. The elevation gyro in the gun sight is mounted with its sensitive axis in the elevation plane. Hence the gyro will measure the angular rate of motion about the elevation axis of the director.

Elevation of the gun sight takes the other gyro, called the traverse gyro, out of the deck plane, the plane in which the director trains, and into a slant plane called the traverse plane, (fig. 10-2C). The traverse gyro measures the angular rate of motion about this axis. Transposition from the traverse plane to the deck plane is accomplished by the director training in the deck plane.

The gyros measure the angular rate about their sensitive axis; but the angular rates are constantly changing, since they are inversely proportional to range. The effect of range on the angular rates used to preduct the lead angles must be considered. The angular rates for a target at its present range are not the same as those at the target's future position.

The second quantity in the lead angle formula is time of flight. It varies nonlinearly with range. This can be seen in column 4 of the range table in chapter 2. Time of flight will increase with range, and obviously the lead angles necessary to hit a target must also increase in proportion to the increase in the



A. TARGET MOTION LEAD ANGLES IN ELEVATION AND TRAVERSE

C. TRAVERSE PLANE

12.216

Figure 10-2.—Lead angle planes.

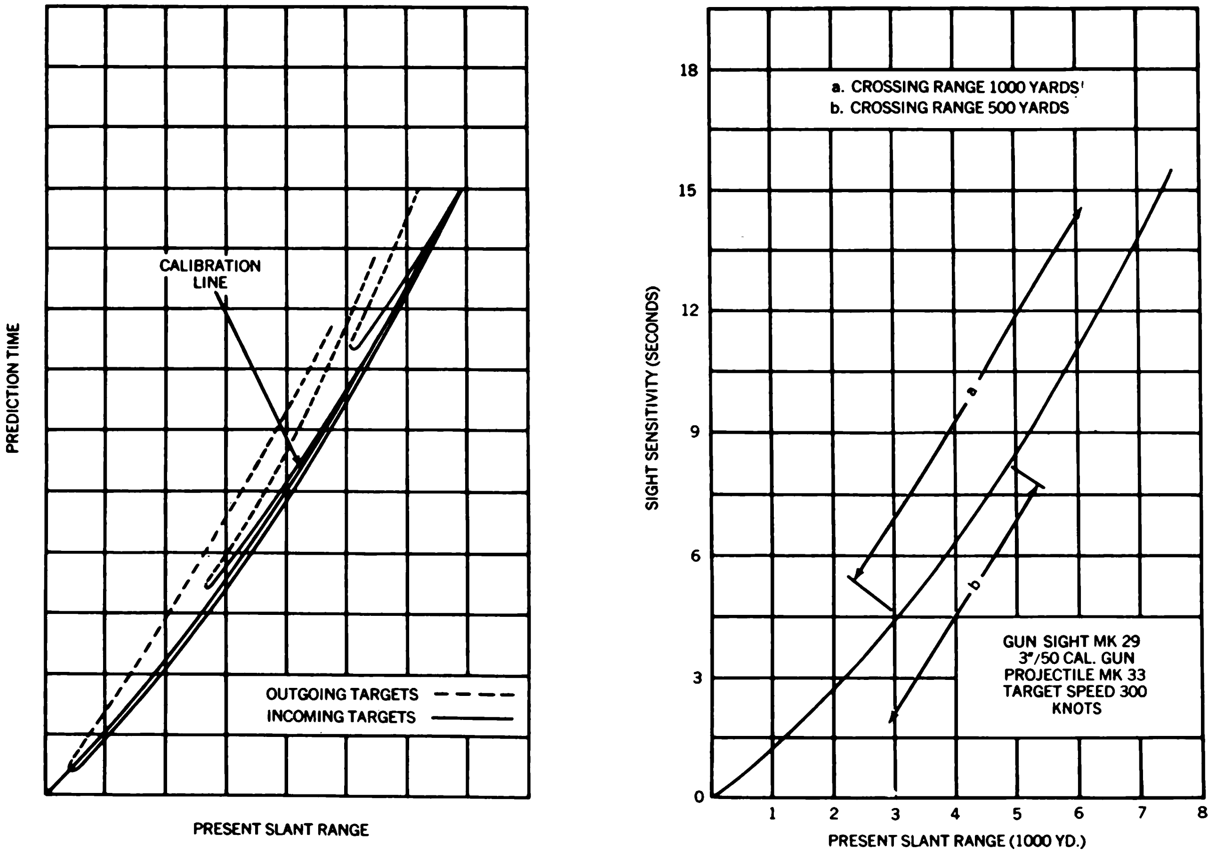
time of flight. Thus both quantities in the lead angle formula vary with range.

A quantity called "Prediction Time", which takes into account the effects of range on the angular rates and the time of flight, is used to solve for the lead angles. Prediction time is a nonlinear function of range, and is obtained from curves. A sample curve is shown in figure 10-3A. The curves were plotted by computing prediction time for a variety of target courses and minimum ranges. Emphasis was placed on incoming targets. A composition of many such curves was used to determine prediction time. Figure 10-3B shows a calibration curve for a lead-computing sight designed for a specific projectile at definite minimum ranges and target speed.

Prediction time is used as a variable restraining force against gyro precession. It therefore governs the sight's sensitivity to angular motion. As range increases, preduction time increases, and the restraint placed on the gyros decreases. At a given angular velocity of the tracking line, the gyros will precess farther at longer ranges. The precession of the gyros due to the angular velocity of the sight's rotation as it tracks a target provides the target motion lead angle. Hence prediction time as a restraint on the gyros governs the amount of lead angle to compensate for changes in angular rates and time of flight due to range changes.

BALLISTIC PROBLEM

The projectile will not hit the target if the gun is pointed directly at the position the target will occupy after the time of flight of the projectile. It is necessary to offset the gun through angles which correct for the effects of gravity, wind, and drift, and for variations in initial velocity of the projectile.



A. PREDICTION TIME VS RANGE

B. SIGHT SENSITIVITY VS RANGE

12.217

Figure 10-3.—A. Prediction time vs range; B. Sight sensitivity vs range.

Gravity, drift, and wind are forces acting on the projectile and deviating its trajectory away from the line of fire. The time of flight governs the amount of time these forces act on the projectile. Time of flight is a function of target range and projectile velocity. Compensation must be made for any change of initial velocity from the standard.

Gravity

Gravity exerts a continuous downward pull, with a force of constant magnitude, perpendicular to the surface of the earth. The force of gravity has a component perpendicular to the line of fire (fig. 10-4A) which pulls the projectile downward and causes it to drop as it travels on its trajectory. To compensate for gravity drop of the projectile, the gun is elevated by an angle called superelevation.

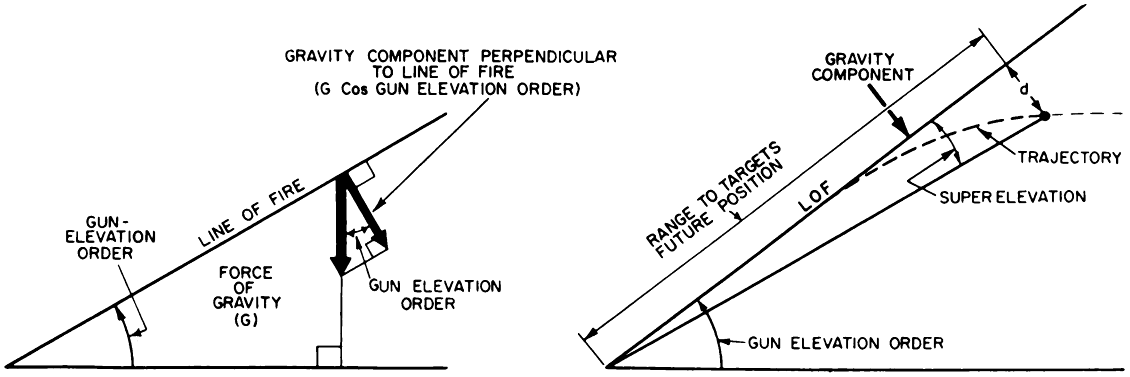
The amount of drop is proportional to the magnitude of the gravity component perpendicular to the line of fire. This is a function of the angle of gun elevation, and varies as the cosine of this angle. As gun elevation increases, the magnitude of the gravity component perpendicular to the line of fire decreases, until at a gun elevation of 90° it is zero.

During the time of flight, the projectile drops below the line of fire through distance "d" in figure 10-4B. If the range were increased, the time during which gravity could act on the projectile would increase and distance "d" would also increase. Therefore, superrelevation is proportional to predicted time as well as to the cosine of the angle of gun elevation.

Drift

The projectile is rotated by the rifling of the gun to obtain the gyroscopic property of rigidity of plane. But with it we must accept the gyroscopic property of precession. The combined action of air resistance, gravity, and gyroscopic action causes the projectile to precess, hence to drift from the line of fire. The direction of drift depends upon the direction of the projectile's rotation. Rotation is normally clockwise, causing the projectile to drift to the right, as shown in figure 10-5. The amount of drift depends on both time of flight and gun elevation. As the time of flight increases, the amount of drift increases. Drift varies as the cosine of the angle of gun elevation. It is maximum at zero° of gun elevation and decreases as gun elevation increases, till at 90°, drift is zero. To compensate for drift the line of fire is offset from the line of sight in train. Since drift is to the right, drift correction is to the left and negative.

The lead angles which offset the line on fire from the line of sight to correct gun elevation for the effects of gravity, and to correct gun train for the effects of drift, are developed in the gunsight. On the gyro's output shafts are weights which apply a twisting force (torque) to the gyros, causing precession. The gyros precess against the restraint of the range springs Therefore the lead angles developed are a function of time of flight. The gunsight case axis is in the line of fire, so the effective weight component acting on the gyro will be proportional to the cosine of gun elevation.



A FORCE OF GRAVITY

B EFFECT OF GRAVITY

12.218

Figure 10-4.—Superelevation.

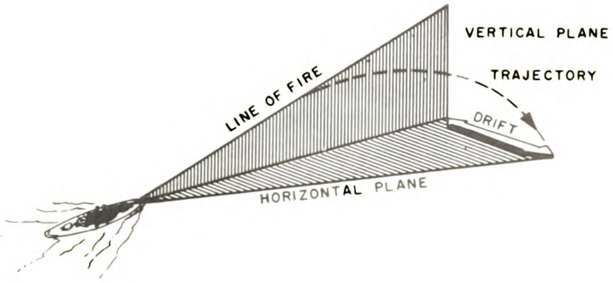


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Figure 10-5.—Drift.

Wind

The wind affecting the motion of the projectile is a combination of the true wind blowing across the surface of the earth and the wind produced by the movement of own ship. True wind is measured from the true north clockwise to the direction FROM WHICH it is blowing; its velocity or force is measured in knots. Own ship's wind is created by the movement of own ship through the atmosphere. Its direction is always the opposite of own ship's course, and its velocity is the same as own ship's speed. The resultant of these two winds is called apparent or relative wind; and it is this resultant wind which deviates the projectile's trajectory away from the line of fire.

APPARENT WIND.—We can obtain apparent wind by vectorially adding true wind and own ship's wind. In figure 10-6 the direction the arrow points indicates the direction of force. It is plotted with the north/south axis as the reference. The length of the line indicates the magnitude of the force. We set up a ratio of length to magnitude: 1 in. = 10 kts. Once established the ratio is constant for the entire vector problem.

A vector can be moved as long as the movement remains parallel to the initial vector. We place the two vector lines head to tail, keeping both the direction and length the same. The resultant force of the two winds is from the tail of the last to the head of the first vector. The arrowhead indicates the direction of apparent wind and the length indicates the magnitude of the force.

The instrument aboard ship used to measure wind direction and velocity is called the anemometer. With the ship underway, this instrument measures apparent wind. It is necessary for us to find true wind by use of vectors. In this case we know apparent wind and own ship's wind. The problem is worked the same way as before but the resultant is true wind. True wind is a relatively constant value when compared to apparent wind. This is because own ship's wind is continuously changing as own ship changes course or speed. To make the wind problem in the fire control instruments independent of ship's course and speed changes, a true wind input is used. If this were not done, a new input of apparent wind would be necessary for each change in ship's course or speed. The information from the anemometer is not smooth enough to be received directly as an automatic input to a fire control instrument. Own ship's movement information is available and can be automatically received in the instrument.

The force of the apparent wind acting on the projectile must be resolved into two components: in and across the line of fire. The component in the line of fire affects elevation and range predictions, while the component across the line of fire affects the traverse prediction. The effect of wind on range prediction is not normally corrected for in the short-range angular system. The correction would be necessary to compute the setting of a time fuze, but this type system uses either the point-detonating or the proximity fuze.

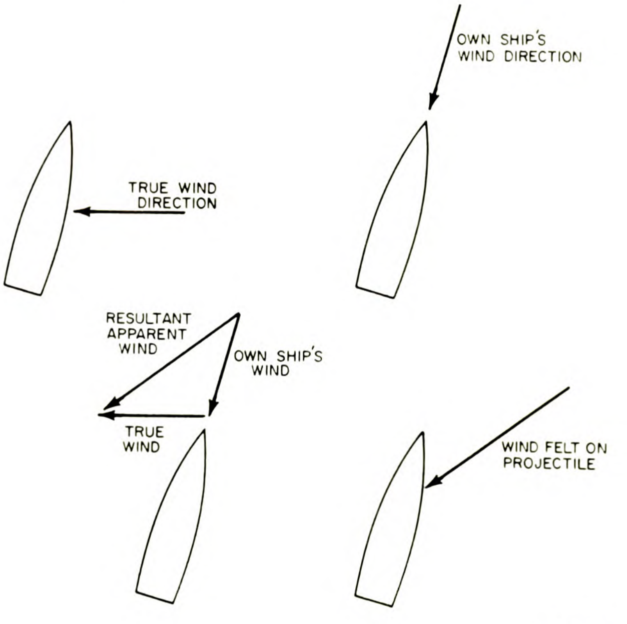

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Figure 10-6.—Apparent wind.

HORIZONTAL WIND COMPONENTS.—We will first consider the apparent wind in the horizontal plane. The wind blowing across the surface of the earth is considered to be in the horizontal plane. Figure 10-7 shows a simplified representation of the problem. The line of fire is established by the gunsight, and we know the apparent wind. By use of the trigonometric functions, sine and cosine, of the angle formed by the intersection of the apparent wind vector with the line of fire, and by the construction of the right triangles, we can resolve the wind force into two components.

TRAVERSE WIND.—The traverse wind component is perpendicular to the line of fire, in the horizontal plane. The wind tends to carry the projectile with it, as shown in figure 10-8. The correction is applied in the gunsight. The amount of correction is equal to the product of the strength of the traverse wind force and the time of flight of the projectile. The correction is accomplished by placing a torque, proportional to the wind force, on the output shaft of the gyro. This torque tends to precess the gyro against the restraint of the range springs. The amount of precession depends on the force applied and the resistance to that force.

ELEVATION WIND.—The range wind in the horizontal plane is the component of apparent wind in the line of fire. If the line of fire is above zero degrees elevation, the range wind will deflect the projectile's path in the vertical plane as shown in figure 10-9. The amount of deflection is a function of the angle of intersection between the line of fire and the range wind vector, and the force of the range wind. The force of the range wind is determined by the apparent wind speed. The angle of intersection is determined by gun elevation. The effect of range wind on elevation is zero at a gun elevation of zero degrees and maximum at 90 degrees. The elevation wind force is equal to range wind force multiplied by the sine function of gun elevation. The elevation wind correction is applied in the sight in the same manner as the traverse wind correction.

Changes in Initial Velocity

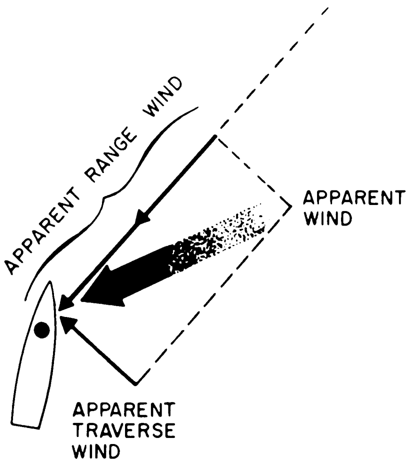
The lead angle computing mechanisms of the gunsight are designed for a standard initial velocity, and any variation from the standard must be compensated for. In chapter 2 we studied the factors affecting initial velocity.

A reduction of initial velocity causes the projectile's time of flight to increase for a given range, making larger lead angles necessary. An increase in initial velocity has the opposite effect. Changes of initial velocity are compensated for by modifying the range input to the gunsight computing units. This is accomplished internally, and affects prediction time. A decrease in initial velocity increases prediction time.

Figure 10-10 shows the total lead angles in elevation and traverse, and the angles that go to make up the lead angles.

LEAD-COMPUTING GUNSIGHT

The simplest lead-computing gunsight has two rate-of-turn gyros mounted 90 degrees apart



12.221
Figure 10-7.—Components of apparent wind.

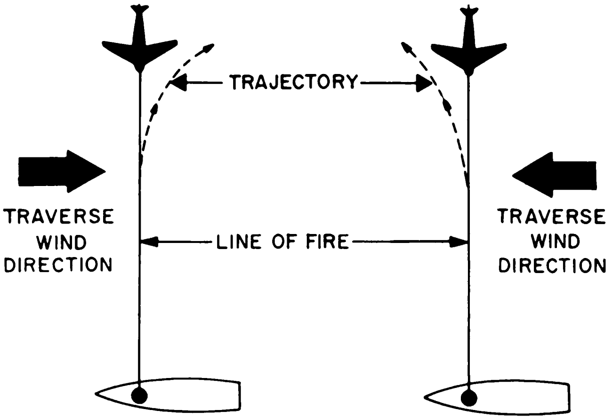


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Figure 10-8.—Effects of traverse wind.

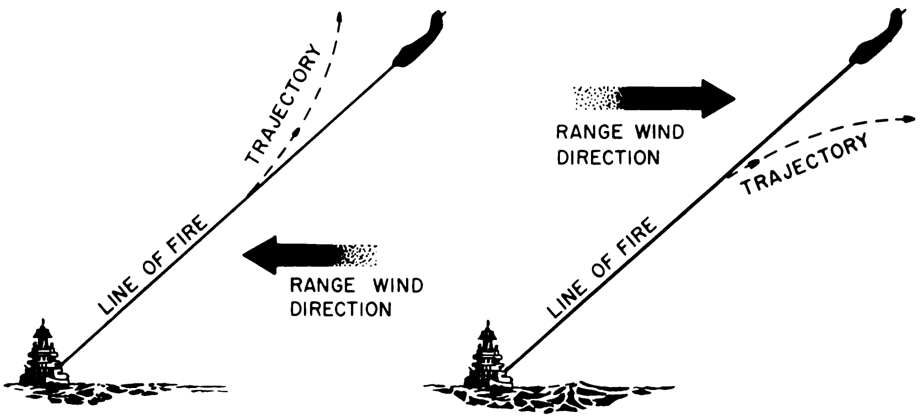

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Figure 10-9.—Effects of range wind.

as shown in figure 10-11. The elevation gyro is mounted so that its spin axis is perpendicular to the base of the sight case. The traverse gyro is mounted with its spin axis parallel to the base of the sight case. Both gyros are restrained in the precession or output axis by the range spring tension. When tracking a target, an external force is applied to the gyro by the movement of the sight, and the gyros react by precessing against the range springs. The amount of precession is determined by angular rate (external force) and prediction time (spring tension). This angle is transmitted mechanically to mirrors by a linkage arrangement (fig. 10-12) which tilts the mirrors. The target image is reflected by the mirrors to the operator's eyes. The tilting of the mirrors offsets the line of sight; the operator repositions the sight to keep the reticle superimposed on the target. This places the sight case axis in line with the future position of the target, while the line of sight continues to point at its present position.

The lead angles are introduced as an offset to the line of sight. When the sight is moved in response to the offset, the sight case axis is automatically positioned in the line of fire. The sight case axis and the gun bore axis are considered to be parallel, and the movement of the sight case axis to be equal to a corresponding motion of the gun bore axis. Systems which introduce the lead angles as an offset to the line of sight in this manner are called Disturbed Line of Sight Systems.

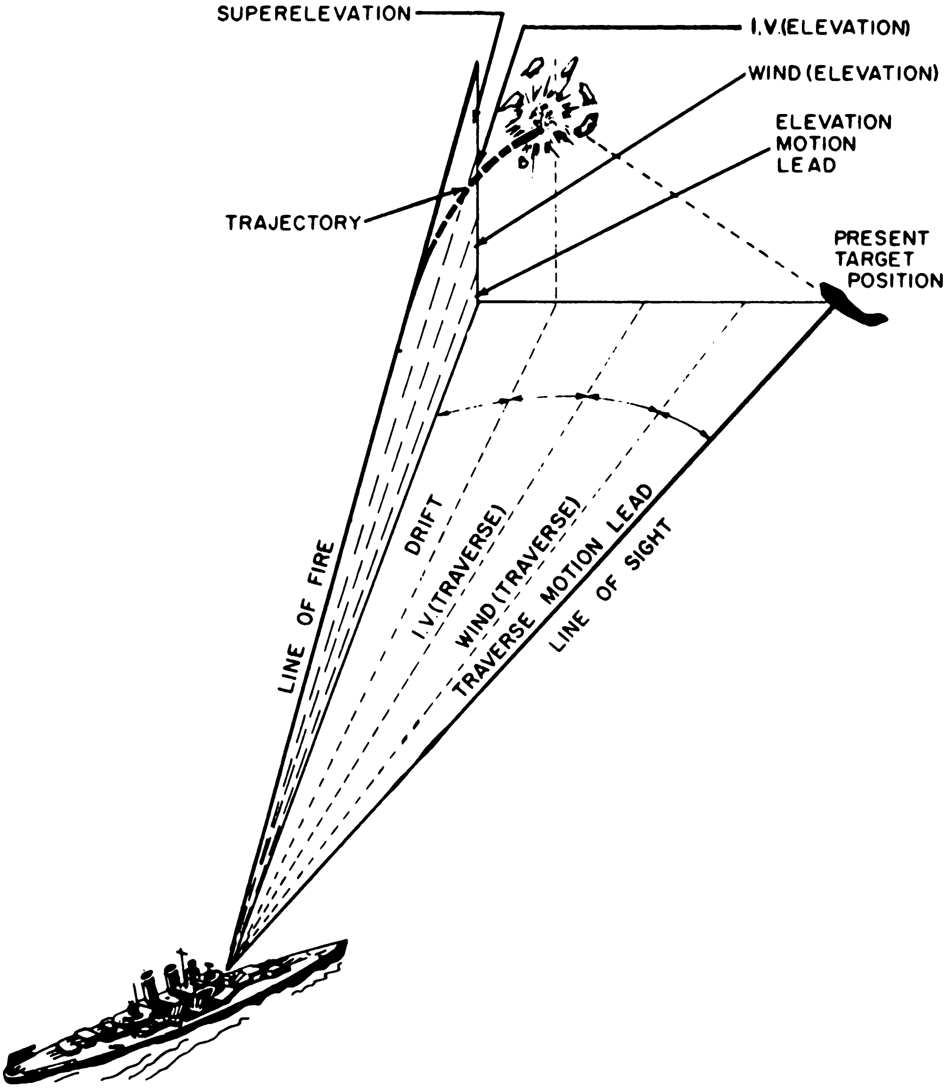
Systems which do not introduce the lead angles at the tracking unit's line of sight are called Undisturbed Line of Sight Systems. The Mk 37, 56, and 68 are examples of this type of system.

GYRO DAMPING

It is essential that the target be tracked smoothly to ensure the generation of correct lead angles in the minimum solution time. To eliminate the generation of false lead angles when slewing the sight to acquire a target, the gyro is locked on zero by a caging device. Hence each tracking problem commences with zero lead angle.

To enable the operator to track the target smoothly, damping of the gyro unit output shaft is essential. The damping supplies a restraining force on the gyro output proportional to the rate at which the lead angle is changing. If the lead angle is not changing, the damping mechanism has no restraining effect and does not influence the angle. Damping causes the gyro to precess slowly and approach the correct lead angle smoothly. It resists lead angle changes caused by small, sudden errors in tracking. Solution time depends on the degree of damping restraint. In figure 10-13A, we see the effect of an underdamped gyro—short solution time but large errors during tracking. Figure 10-13B shows the effect of an overdamped gyro—long solution time with small tracking errors. Figure 10-13C shows the effect of the damping restraint actually used in the sight—medium solution time with medium tracking errors. Damping in the gunsight is similar to negative feedback in a servoamplifier.

Damping is accomplished by a disk (fig. 10-14) attached to the output shaft of the gyro



12.224

Figure 10-10.—Lead angle components.

in a housing containing a viscous (resistant to flow) fluid which resists the rotation of the disk. The amount of resistance the fluid offers depends on its temperature. The fluid is heated electrically, and its temperature is controlled by an adjustable thermal switch.

When radar is a part of the system, provisions are made to enter radar train and elevation information into the optical system. This enables the system to track a target when it is not visible; this is called blind tracking. The gunsight operation is the same for both visual and blind tracking. The radar furnishes range information to the sight.

The optical system of the sight contains a filter to reduce glare when a target is tracked near the sun, or against a bright background. For radar tracking, the filter provides a dark background against which the radar video information can be seen clearly. The reticle is illuminated for tracking against dark backgrounds at night. The intensity of the illumination, and of the radar presentation, are controlled by the operator.

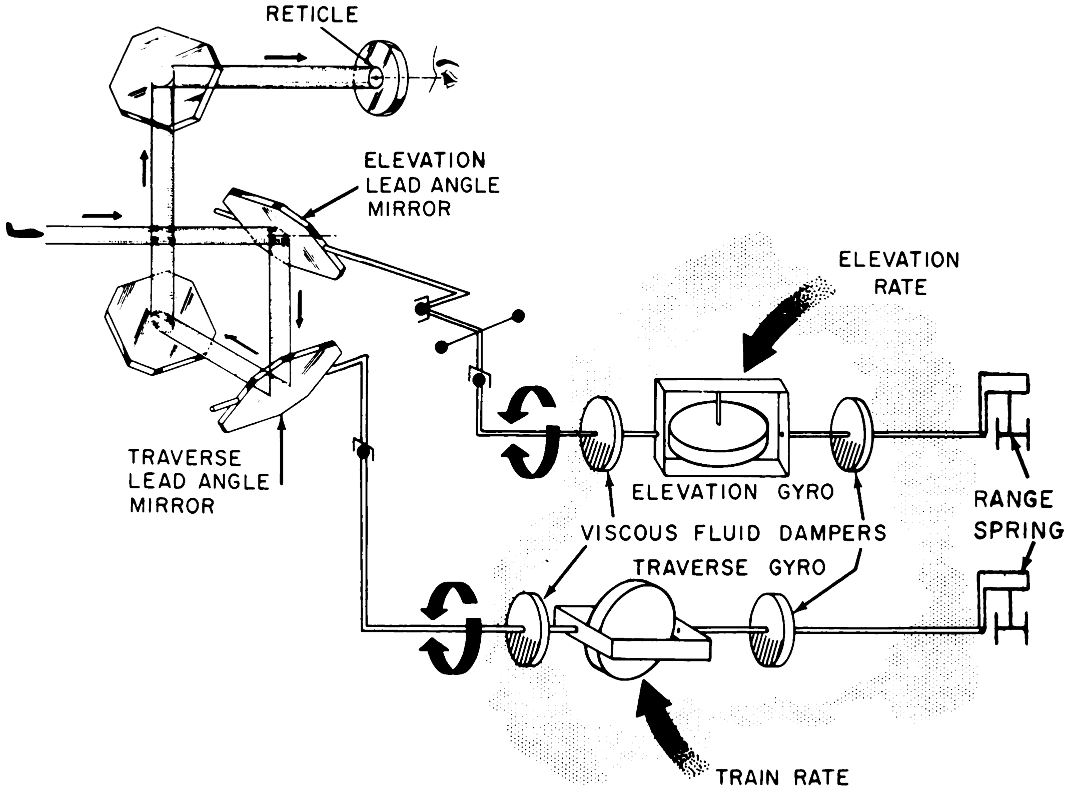


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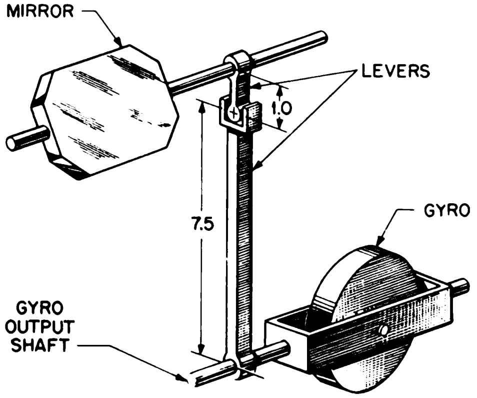
Figure 10-11.—Gunsight gyros and mirror system.

The controls at the gunsight are: the initial velocity, range and range rate inputs, power switch, illumination, radar intensity, filter, caging, and gun firing circuit.

The initial velocity is a manual input. This is normally computed and set before or upon initially manning the station. Range and range rate are normally received automatically from the radar but these quantities can be manually set at the gunsight.



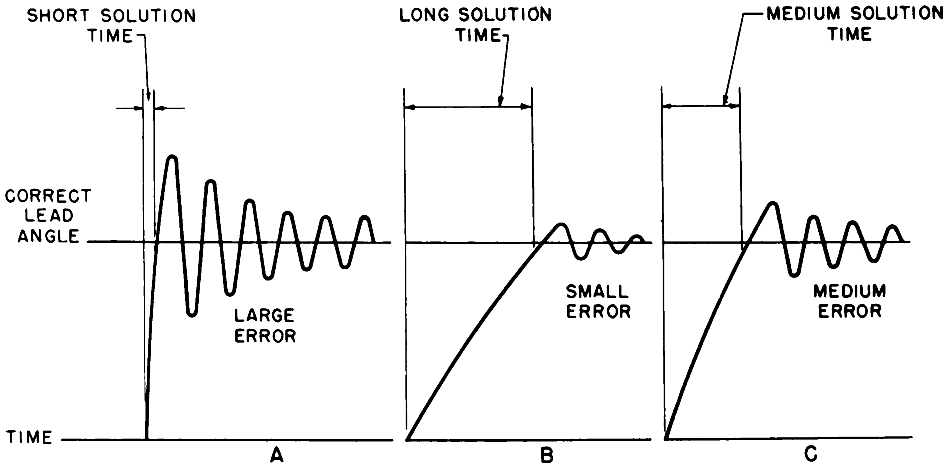
12.227

Figure 10-12.—Gyro lever arrangement.

TWO-DEGREE-OF-FREEDOM GYRO SIGHT

Some lead-computing sights use a two-degree-of-freedom gyro instead of two rate gyros. The gyro is an electric motor whose relatively heavy moving parts correspond to the gyro wheel. This arrangement is similar to the gyro used in the stable element discussed in chapter 9. The gyro is mounted on pivot pins in a gimbal, as shown in figure 10-15, and the gimbal is mounted on pivot pins to the sight case. Hence the gyro can be tilted up or down about the gyro pivots and can be moved right or left about the gimbal pivots.

The gyro spin axis tends to remain fixed in space when the gyro motor is running. Hence, when the sight is moved, as in tracking a target, the sight case moves about the gyro spin axis. But, as you know, the spin axis can be moved in



12.228

Figure 10-13.—Effect of damping.

any direction if a properly directed torque is applied to the gyro or the gimbal. The main precessing force is exerted by the range magnet, which is mounted on the sight case directly in front of the gyro, (fig. 10-16). The eddy-current disk in the figure is attached to the gyro shaft, and rotates with the gyro. The magnet's pole piece is located close to the eddy-current disk. The disk thus rotates in a magnetic field set up by electric current in the windings of the range magnet.

When an electric conductor, the disk, is moved in a magnetic field, electric currents are induced in the conductor. In accordance with Lentz's law, a magnetic field is set up about the induced eddy currents which is in opposition to the magnetic field set up by the magnet. The interaction of the magnetic fields results in a force being applied to the disk and hence to the gyro motor. When the magnet pole piece is aligned with the center of the disk the force exerted is concentric with the gyro spin axis and will not cause the gyro to precess. In this condition the gyro spin axis, the magnet pole piece axis, and the line of sight are parallel.

But suppose that the sight case, and therefore magnet, are moved to the left as shown in figure 10-17. Since the part of the disk opposite the magnet pole is moving up, the force exerted by the interaction of the magnetic fields is in a

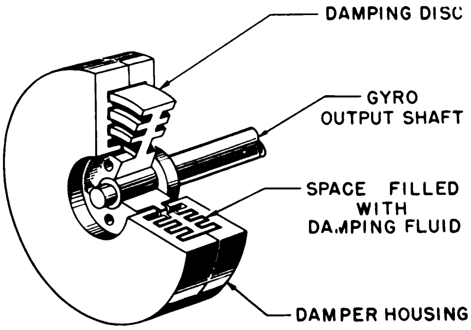


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Figure 10-14.—Gyro damper.

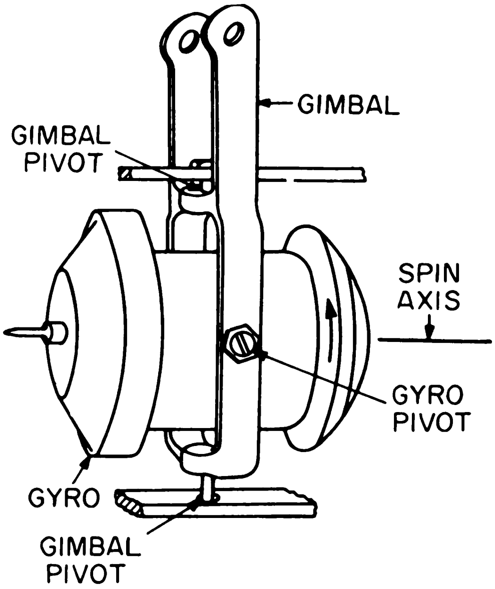

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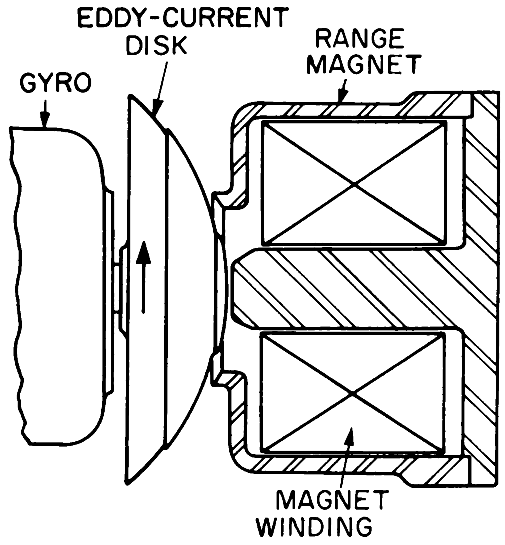
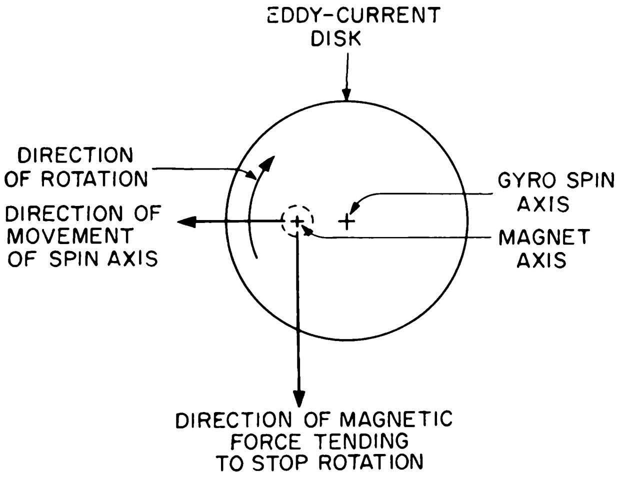
Figure 10-15.—Gyro and gimbal.



12.293
Figure 10-16.—Range magnet and eddy-current disk.

downward direction. The downward force will cause the gyro to precess to the left as shown in the figure. The gyro spin axis follows the movement of the magnet. The same result occurs when the sight case is moved in any direction; the gyro axis will always follow the magnet axis and the line of sight.

The speed at which the gyro precesses to follow the magnet depends on the strength of the torque exerted by the magnet. If the torque increases, the precession rate increases; if the torque decreases, the rate will decrease. If the torque is uniform the gyro axis will follow the magnet axis at a uniform rate.


EDDY-CURRENT DISK
DIRECTION OF ROTATION
DIRECTION OF MOVEMENT OF SPIN AXIS
GYRO SPIN AXIS
MAGNET AXIS
DIRECTION OF MAGNETIC FORCE TENDING TO STOP ROTATION

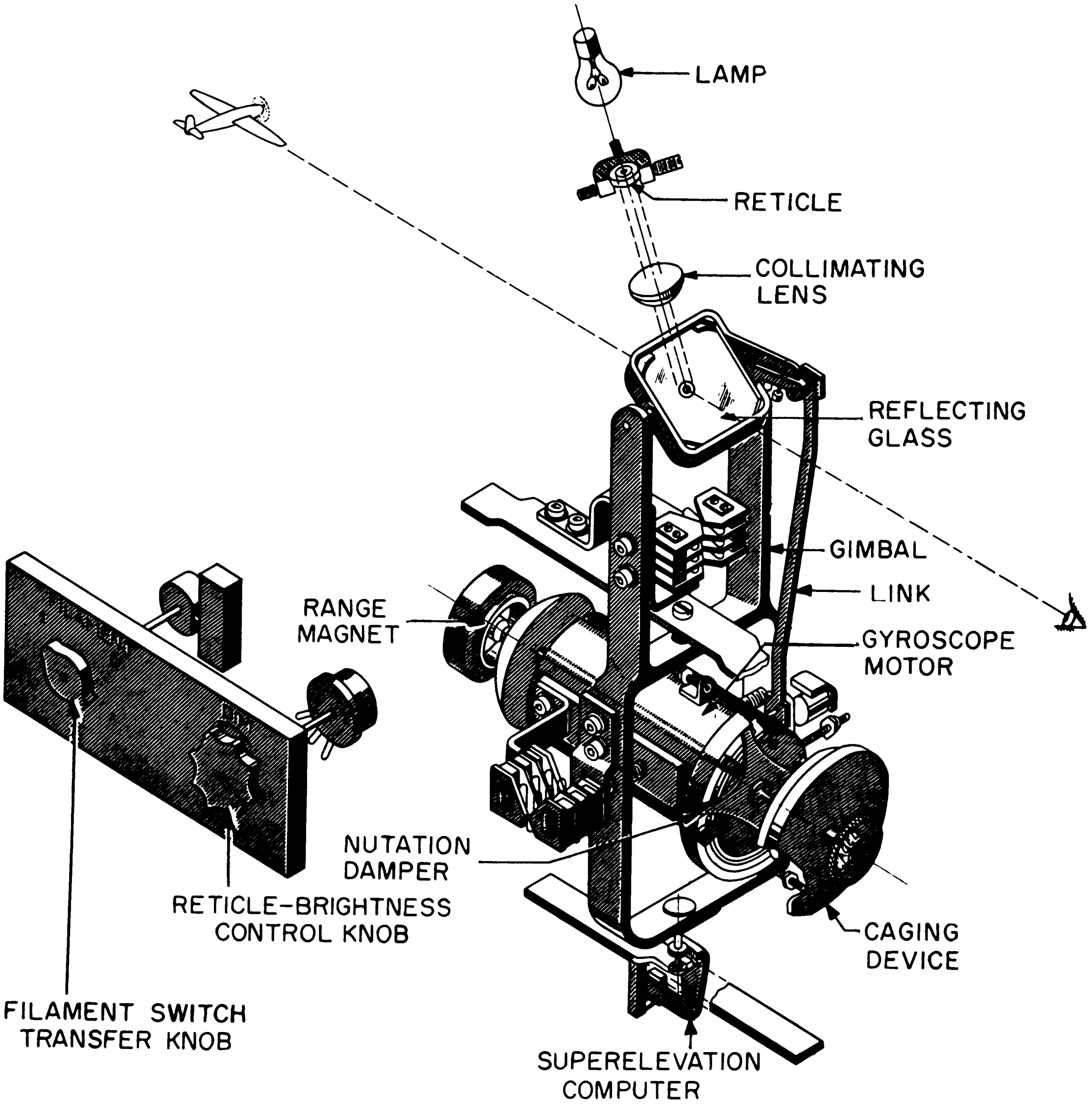
12.294
Figure 10-17.—Gyro follows magnet.

The strength of the precessing force is determined by the amount of the magnet's current and by the offset of the magnet from the center of the eddy-current disk. The force is zero when the magnet is at the center of the disk, but the force increases steadily as the magnet moves away from the center. If the magnet has a uniform current, and is moving at a uniform speed, it must move through a definite angle from the center of the disk before the gyro will move at the same speed. The gyro then will follow the magnet, but with a definite angle of lag. This angle will not change unless the magnetic coupling between the magnet, which moves with the sight case, and the gyro, which tends to remain fixed in space, is changed.

The angle of lag of the gyro will increase with an increase in the speed of movement of the magnet, and it will be reduced if the magnet is moved at a slower speed. Since the magnet is mounted on the sight case, it is the angular rate of the line of sight which controls the amount of gyro lag. The direction of the gyro lag indicates the direction of the target's movement.

The gyro lag can also be controlled by a change in the magnet's current. An increase in current will increase the torque and hence reduce the gyro lag necessary to move the gyro at the same angular rate as the line of sight. The range circuit in the sight supplies the magnet current. This current is inversely proportional to range. At longer ranges the current is reduced and the gyro's angle of lag will increase. The range current and the magnetic coupling between the disk and the magnet are comparable with the range spring arrangement in the rate gyro sights.

Figure 10-18 shows the general arrangement of the components in the sight. The reflector glass is mounted on the gyro gimbal and moves with it to the right and left. The glass is free to pivot up and down in its mounting, and is connected to the gyro in this axis by the bar link. When a target is being tracked, the reflector glass follows the gyro spin axis. The angular displacement of the range magnet and the gyro spin axis will increase until the resultant force of the magnetic field is sufficient to impart a rate of precession to the gyro equal to the tracking rate of the line of sight. When the two rates are equal, the angle between the gyro spin axis and the sight case axis is equal to the



12.295

Figure 10-18.—Components of gun sight.

target motion lead angle required to hit the target.

LIGHT

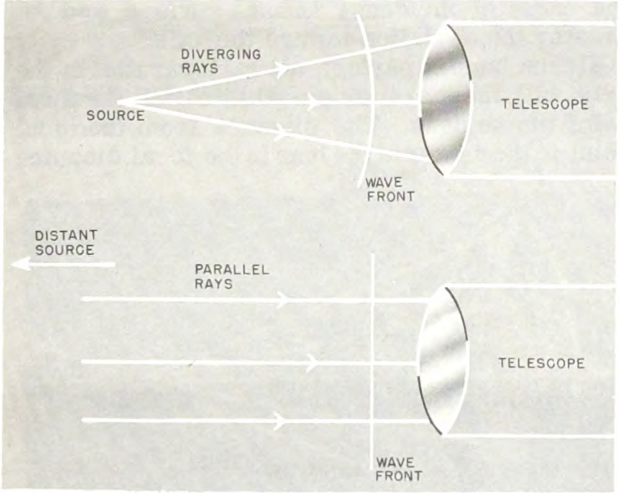
Before going into the optical system, we will briefly examine some of the properties of light. To start with, light is a form of energy. It travels in wave form, and is identical with other types of electromagnetic radiation except for wavelength and frequency. The color of visible light depends on its wavelength—violet having the shortest and red the longest wavelength. Radiation of longer wavelength than visible red is called infrared or heat radiation. Beyond infrared are the radio waves. Radiations shorter than visible violet are, in the order of decreasing wavelength: ultraviolet, X rays, gamma rays, and cosmic rays.

If a small object is dropped in water, a series of concentric circular waves will spread out from the point of impact. This provides a familiar analogy for the behavior of light waves. The wavelength is the distance from the crest of one wave to the crest of the next. The frequency is the number of waves that pass a given point in unit time. The waves that move outward from a source of light may be thought of as a series of concentric, rapidly expanding spheres.

In the study of optical instruments, it is convenient to trace the path of light rays rather than waves. A light ray is an imaginary line used to show the direction in which the light wave is moving. A ray is a radius of the sphere formed by the wavefront, and is at right angles to the wavefront. Although there is an infinite number of rays in a spherical wave, usually three rays are enough to show the path of light and the formation of an image in a diagram of an optical instrument.

A telescope or similar instrument will receive only a small part of the light emitted by the source. Each wave that enters the instrument, therefore, is only a small part of a sphere. If the wave comes from a nearby source, the part of it that enters the instrument will be strongly curved and the rays will be diverging (fig. 10-19). But if the source is at a great distance, the part of the wave that enters the instrument will be nearly flat; for all practical purposes the rays can be considered to be parallel. The latter is the case in our optical system.

A target or other object is visible when it reflects light towards the observer. If the object is large, not all the rays that enter the instrument will be parallel. But each point on the object may be considered a point source of light, and all the rays that enter from any one point will be parallel.



12.230
Figure 10-19.—Light rays from nearby and distant source.

Reflection

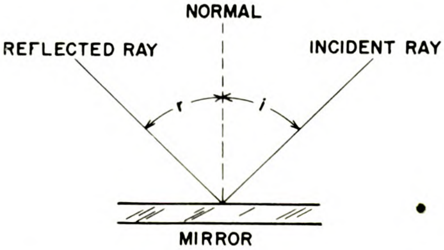
Figure 10-20 illustrates several of the terms used to describe the reflection of light. The incoming ray, from the source, is the incident ray. The normal is an imaginary straight line at right angles to the reflecting surface (in this case a mirror), passing through the point of incidence. The angle of incidence is the angle between the incident ray and the normal, and the angle of reflection is the angle between the normal and the reflected ray. The law of reflection states, first, that the angle of incidence is equal to the angle of reflection; and, second, that the incident ray, the reflected ray, and the normal all lie in the same plane.

When light strikes the surface of clear glass, a part of the light will be reflected and the rest will enter the glass. If the incident ray lies on the normal (zero angle of incidence) about 5 percent of the light will be reflected. As the angle of incidence is increased the amount of reflection increases. As the angle of incident approaches 90°, the reflection approaches 100 percent.

In the gunsight, mirrors are used to deviate the line of sight. The radar presentation of target's relative position is entered into the optical system by use of a semitransparent material that will reflect some of the light from the radar cathode-ray tube to the operator's eye.

Refraction of Light

Light travels at a speed of approximately 186,000 miles per second in air. In a vacuum, its velocity is slightly higher. In a denser medium it moves more slowly. When light passes from one medium into another of different



12.231
Figure 10-20.—The angle of reflection is equal to the angle of incidence.

density, its velocity changes. This change in velocity makes it possible for an optical instrument to control the path of light, to form images and to magnify them.

In figure 10-21 a ray of light strikes a glass at an oblique angle (any angle which is not a right angle). The approaching light waves are from a distant source, and are therefore parallel. As each wave enters the glass, various points along the wave front will slow up successively, and as a result the entire wave front will change its angle. Since the direction of movement, shown by the ray, is at right angles to the wave fronts, the light bends as it enters the glass. The opposite effect occurs when the waves leave the glass. Now the various points along the wave successively increase their speed. As a result, the emergent waves are parallel to those that entered the glass. And the emergent ray is parallel to the incident ray, although it has been displaced to one side.

Figure 10-22 illustrates some of the terms used to describe the refraction or bending of light. The law of refraction states that light bends toward the normal when it passes into a denser medium; it bends away from the normal when it passes into a less dense medium. The exact angle of refraction depends on the angle of incidence, and on the optical density of the two media. (The index of refraction of a vacuum is one.)

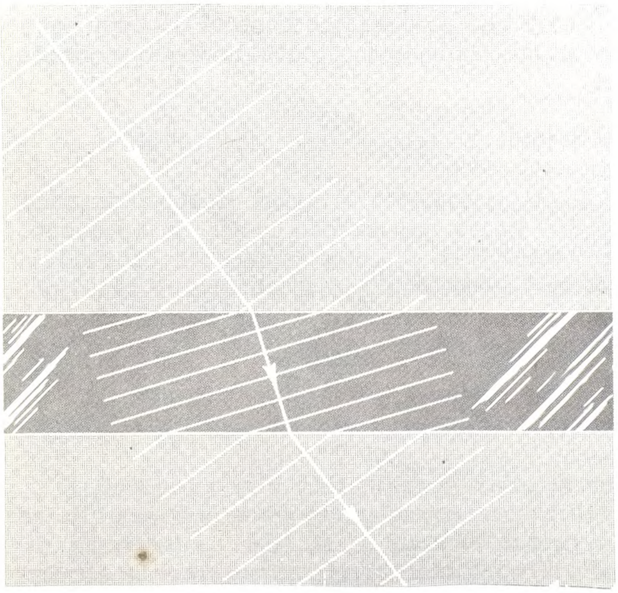


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Figure 10-21.—Path of wave fronts through a sheet of glass.

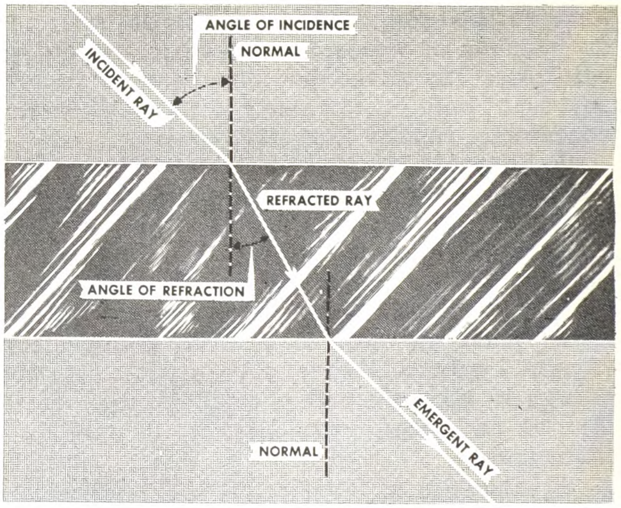

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Figure 10-22.—Terms used to describe the refraction of light.

Figure 10-23 shows the path of parallel rays of light on passing through a convergent lens. Each ray will have a different angle of incidence, and will therefore bend to a different degree. The ray that passes through the center of the lens is normal to both surfaces, and therefore does not bend. Rays near the axis will strike each surface at a small angle of incidence and will be slightly deviated toward the axis. The greater the distance from the axis, the greater the angle of incidence at each surface, and the greater the deviation toward the axis.

If the lens is perfect, all rays parallel to the axis will meet at a single point called the focal point of the lens. The distance from the focal point to the center of the lens is the focal distance

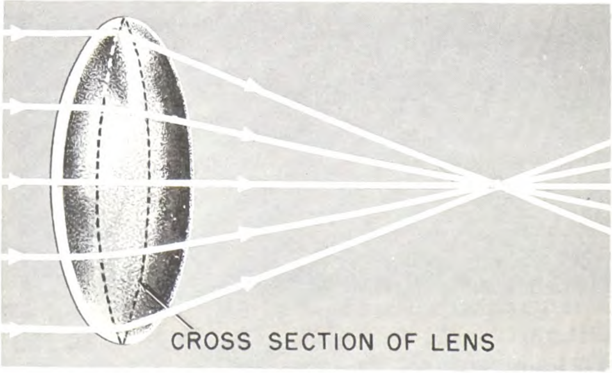


Figure 10-23.—Deviation of rays by a convergent lens. 12.234

or focal length of the lens. The focal length of a lens in an optical instrument governs the magnification factor of the instrument.

The laws of reflection and refraction are laws of transverse wave transmission of energy. It is interesting to note that they hold true for all energy that travels in wave form, which also includes other electromagnetic waves. Radar antennas are a good example of reflection, with the feed horn as the source and the disk the reflector. Sonar systems have to deal with reflection and refraction of sound waves caused by the variations in density of the thermal layers of the ocean.

OPTICAL SYSTEM

We will use Gunsight Mk 29 Mod 1 as a typical gunsight to illustrate the basic principles. The optical system applies the lead angles by using the tilt of the traverse and elevation gyros to offset the line of sight from the sight case. For ''blind'' tracking, or acquiring targets when visibility is limited, a radar presentation introduced into the field of view replaces the telescopic image.

The line of sight from the target is reflected by each of four mirrors (fig. 10-24). The two lead-angle mirrors are controlled by the two gyros, so that the optical line of sight lags behind the sight case axis when the sight is moved. The two spotting mirrors are used to align the gun sight to the director, and during certain tests that are run on the gunsight.

Since the target is always at a relatively great distance from the sight, the light rays from the target are in effect parallel, or collimated. The rays of light, in passing through the objective lens, are refracted to converge and to focus on the reticle plate. The light from the image on the reticle plate, and from the reticle itself, is again made parallel by the eyepiece lenses before reaching the director pointer's eye. The reticle lens is at the focal plane of the telescope eyepiece lenses; therefore the pointer sees the reticle superimposed on the target image, and apparently located at the same distance as the target.

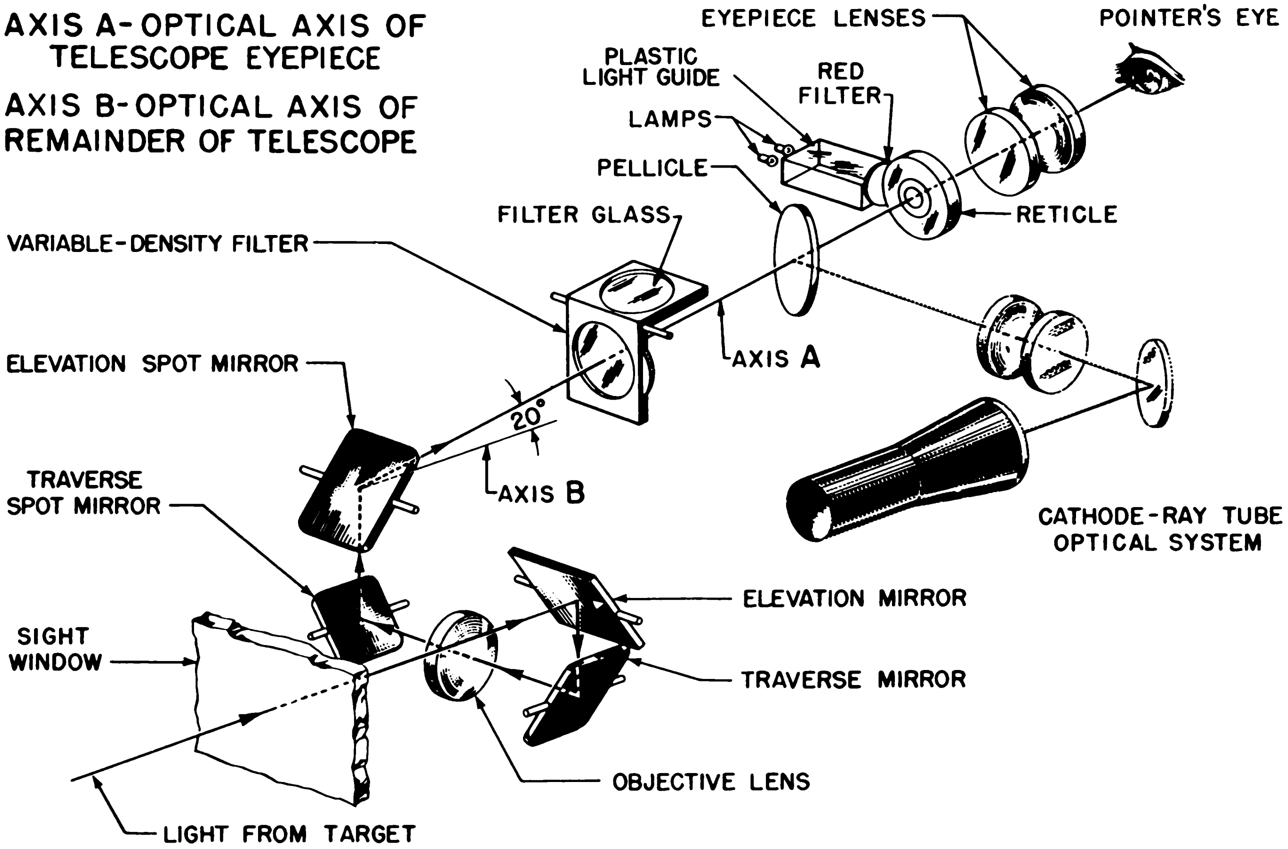


Figure 10-24.—Gunsight optical system.

12.235

The filter bracket holds a pair of polaroid filters. One of these is stationary, and serves to decrease the glare from sky and water. The other polaroid filter may be rotated with respect to the first filter; the amount of rotation controls the image brightness. When the filters are not needed, they may be swung out of the line of sight, and replaced by a lens of clear glass.

The pellicle is a plastic disc, coated with a thin semitransparent film. It has no effect on the target image, except to decrease its brightness somewhat.

The cathode-ray tube is used for blind (radar) tracking. The radar indication appears as a spot on the face of the cathode-ray tube. The light from this spot is reflected by the mirror, and passes through the cathode-ray objective lens. It is then reflected by the pellicle, back toward the eyepiece. When the axis of the radar antenna is pointed directly at the target, the spot appears to be centered in the reticle. When the target moves off the radar axis, the spot moves toward the side of the tube. The sight operator tracks the target by keeping the spot centered on the reticle.

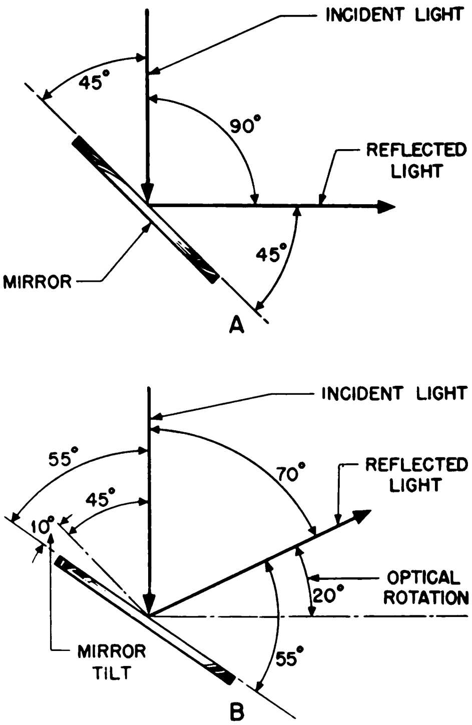
Introduction of Lead Angle

The line of sight is offset from the sight case by rotation of the traverse and elevation mirrors. Each mirror is connected to its gyro by levers (fig. 10-12) which transfer the tilt of the gyro to the mirror. Since the ratio between the lengths of the levers is 7.5 to 1, the tilt of the mirror is 7 1/2 times as great as the tilt of the gyro.

When a mirror is rotated, the reflected light moves through an angle twice as great as the motion of the mirror. If incident light strikes a mirror at 45° (fig. 10-25A), the light is reflected at an angle of 45 degrees with the surface of the mirror. The angle between the incident and reflected light is 90 degrees.

If the mirror is tilted 10°, so that the incident light strikes the mirror at 55° (fig. 10-25B) the light is reflected at an angle of 55° with the surface of the mirror. The angle between the incident and reflected light is 70 degrees. The 10° tilt of the mirror produces a 20° change in the angle between the incident light and reflected light.

The multiplication factor of the mirror and linkage is a total of 15. Because of this, the gyros move through an angle only 1/15 as great as the angle through which the line of sight is offset.



12.236
Figure 10-25.—Optical multiplication of mirror.

GUN ORDER TRANSMISSION

The lead angles accounting for target motion and ballistics offset the line of sight, so that the sight case is displaced from the line of sight and points along the line of fire. In tracking, to keep the offset line of sight on the target, the sight case is moved in both train and elevation. The gun is positioned along the line of fire by a gun order transmission system which sends the train and elevation of the sight case to the gun mount. This information is also sent to any instrument in the system that requires it.

If the director and gun are separated by a horizontal fore-and-aft distance greater than 10 yards, gun-train order is not sent directly to the gun mount. It is sent to a gun order corrector where it is corrected for horizontal parallax. Gun elevation is transmitted directly to the gun mount. Gun orders are transmitted by synchros (which were covered in chapter 7 of this course).

CROSS-ROLL

The sight operator, in keeping on the target, becomes the system's stable element in that he corrects for the roll and pitch of the ship. However, the damping devices which smooth the gyro movements in tracking cause the gyros to lag when the angular rates change. In normal tracking, the errors resulting from the lags are accounted for by sight calibration. If the gunsight rotates about the line of fire, secondary lags occur and errors are produced. The errors resulting from the secondary lags are called cross-roll errors.

Rotation About Line of Fire

Rotation of the gunsight about the line of fire may occur when the sight is moved by tilting of the deck, or when it is trained while it is elevated. Rotation about the line of fire is measured in a plane perpendicular to the line of fire.

If the deck tilts (fig. 10-26), causing the gunsight to be rotated about the line of fire, the planes in which the gyros measure the rates tilt with the deck. The gyros then tend to interchange functions. The elevation gyro measures part of the rate formerly measured by the traverse gyro, and the traverse gyro measures part of the rate formerly measured by the elevation gyro. If the gunsight were rotated 90° about the line of fire, a complete interchange of function would take place.

The interchange of gyro function is not instantaneous; damping causes the gyro to lag behind the changes in angular rates due to rotation about the line of fire, and to generate incorrect lead angles.

An additional component of rotation about the line of fire, and in the plane perpendicular to it, is caused when the sight is trained with the sight case elevated.

Plane P (fig. 10-27A) passes through the intersection of the train axis and the line of fire, and is perpendicular to the line of fire. Line A is a reference line in plane P. Line A and plane P move with the sight case. A rotation of the sight case about the line of fire is indicated if line A has an angular rate in plane P about the line of fire.

When the director is trained with the sight elevated, line A moves about the train axis in a cone. The instantaneous direction of motion of line A is linear in plane P (fig. 10-27B). However, line A is moving with its lower end at the train axis, and the path of line A has an angular rate in plane P. The angular rate of A in plane P

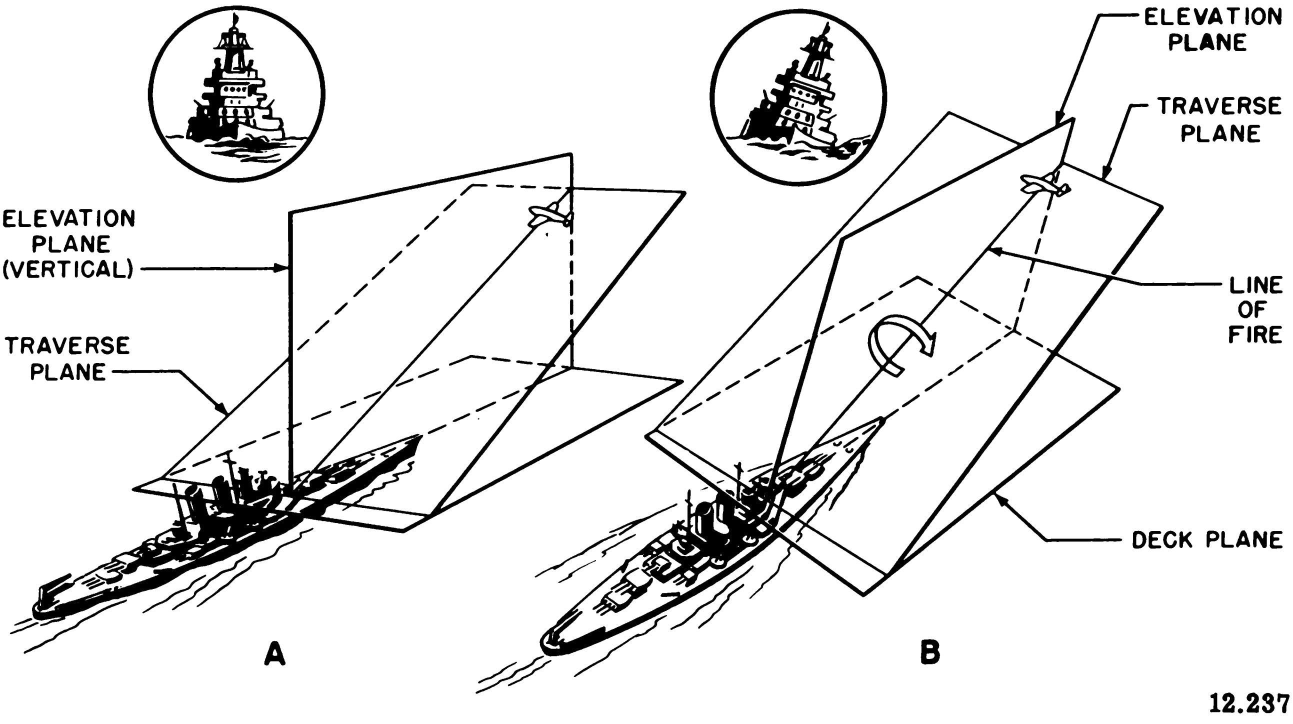


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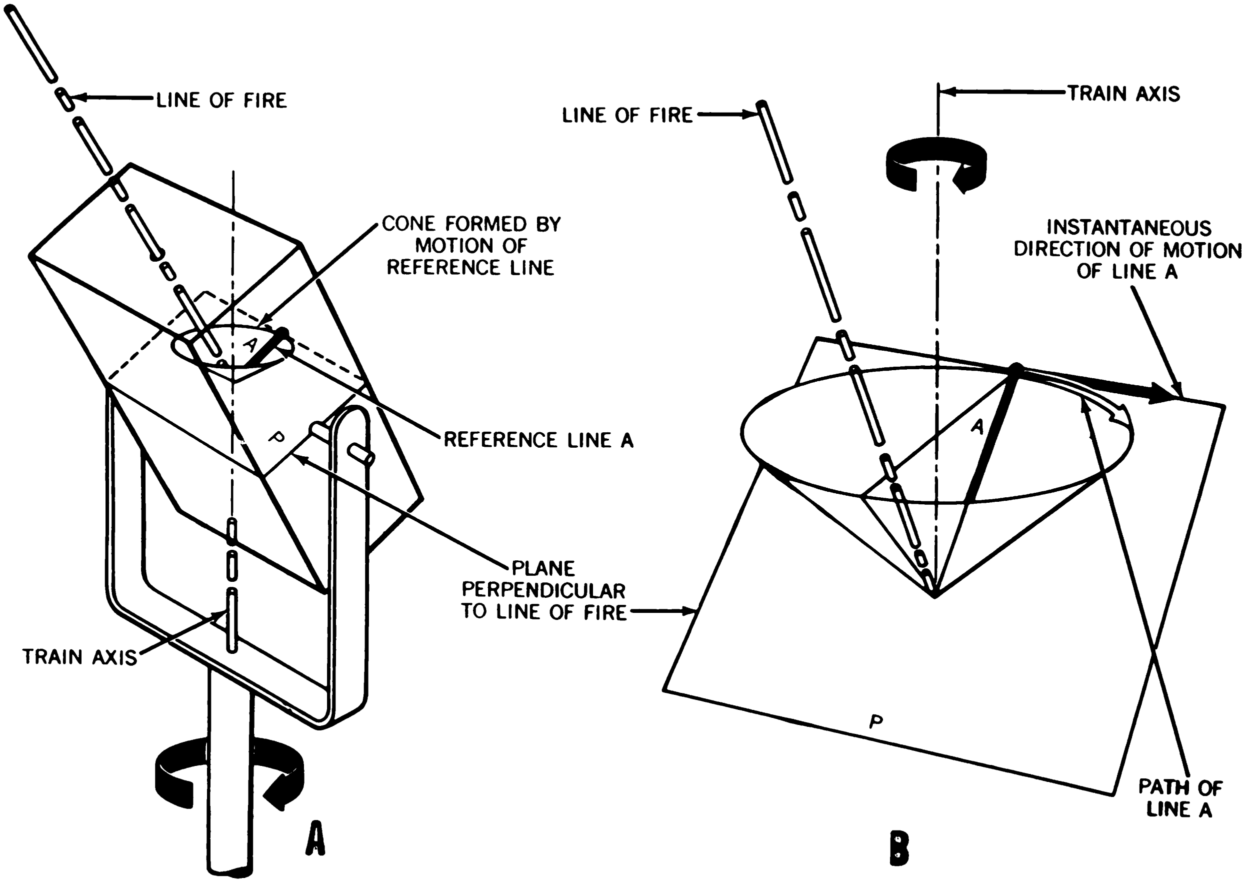
Figure 10-26.—Rotation about line of fire due to tilting deck.


LINE OF FIRE
CONE FORMED BY MOTION OF REFERENCE LINE
A
P
REFERENCE LINE A
PLANE PERPENDICULAR TO LINE OF FIRE
TRAIN AXIS
A
LINE OF FIRE
TRAIN AXIS
INSTANTANEOUS DIRECTION OF MOTION OF LINE A
A
P
PATH OF LINE A
B

12.238

Figure 10-27.—Rotation about line of fire due to train.

at any instant is the rate at which the sight case is effectively rotating about the line of fire.

The rotation of the sight case about the line of fire in plane P produces errors in lead angle identical to those produced by motion of the deck.

Cross-Roll Gyro

The rate at which the sight case rotates about the line of fire is measured by a rate-of-turn gyro called the cross-roll gyro. In the GFCS Mk 63, using a Gunsight Mk 29, the cross-roll gyro is located in the director head. It is mechanically coupled to keep the cross-roll gyro parallel to the line of fire. The gyro spin axis is perpendicular to the traverse plane. The output axis is perpendicular to the line of fire, and responds to components of cross-roll by precessing through an angle proportional to the rate of rotation about the line of fire. The damping applied to smooth the action of the gyro is slight, permitting the gyro to respond quickly to movements in cross-roll.

Cross-roll errors are eliminated by torques which oppose the damping produced when the traverse and elevation gyros interchange functions. The aiding torque applied to one gyro is proportional to:

1. the rate of rotation about the line of fire.
2. the magnitude of the lead angle on the other gyro.

The aiding torque on the gyro is made proportional to the rate of rotation about the line of fire, because the greater the rate of rotation, the more rapidly the gyros must interchange function. The aiding torque is made proportional to the opposite lead angle to make the speed with which the gyros interchange function proportionate to the size of the lead angle to be measured. When a gyro is to assume a large lead angle, the aiding torque is sufficiently great to cause a rapid interchange of function.

The direction and amount of the rotation of the gunsight around the line of fire is measured by the cross-roll gyro. This is converted to an electrical measurement by a device called the pickoff transformer. The core of the transformer is movable, and is positioned by the output shaft of the gyro. By moving the core between the windings, we can control the phase and the magnitude of the output voltage. The phase of the output voltage is determined by the direction of precession, and the magnitude by the amount of pression. If the gyro is not precessed, the output voltage is zero. The same type of device is used to obtain an electrical measurement of the elevation and traverse lead angles (fig. 10-28).

The three signal voltages are amplified. The amplified voltage from the cross-roll gyro is applied to one set of the windings of the torque motors on the output shafts of the gyros. The other winding is supplied with the amplified lead angle voltage at the other gyro. The torque motor generates a torque whose magnitude is proportional to the product of the two voltages on its winding, and whose direction is determined by the phase relationship between the voltages. This torque is applied to the output shaft of the gyro and is used to instantaneously overcome the damping of the gyro. The gyro can therefore measure the correct lead angle smoothly, even though the sight case is rotating around the line of fire.

GUN FIRE CONTROL SYSTEM MK 63

The GFCS Mk 63 is a typical relative-rate system, which we will use here to apply the

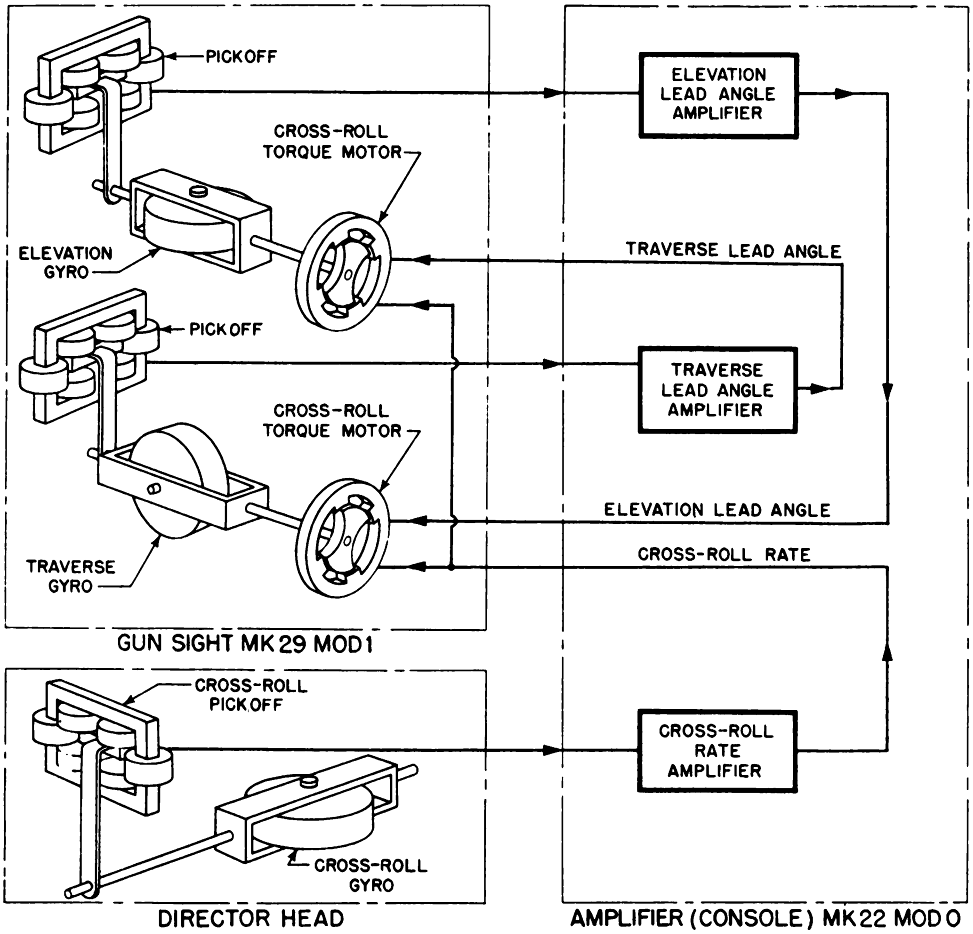


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Figure 10-28.—Cross-roll correction system.

basic principles of lead computing to a complete system. Figure 10-29 is a simplified flow diagram of the system. The brief description of the major units is arranged to follow the flow of information from the director to the gun mount. The gunsight, director pedestal, antenna mount, and in some instances the air supply unit, are located topside. All other units are installed below decks.

The director pedestal supports the gunsight, moving it in train and elevation as the director handles are moved by the director pointer. The director pedestal consists of two principal *units*, the stand assembly and the head assembly. The stand assembly is bolted to the deck and support the head assembly. The head assembly is th rotating section of the director. The directo transmits gun-train order, gun-elevation order and true director elevation.

The gunsight contains the gyros for travers and elevation, and computes the lead angle t compensate for relative target motion an ballistics. The gunsight receives range, range rate and wind correction information, and when

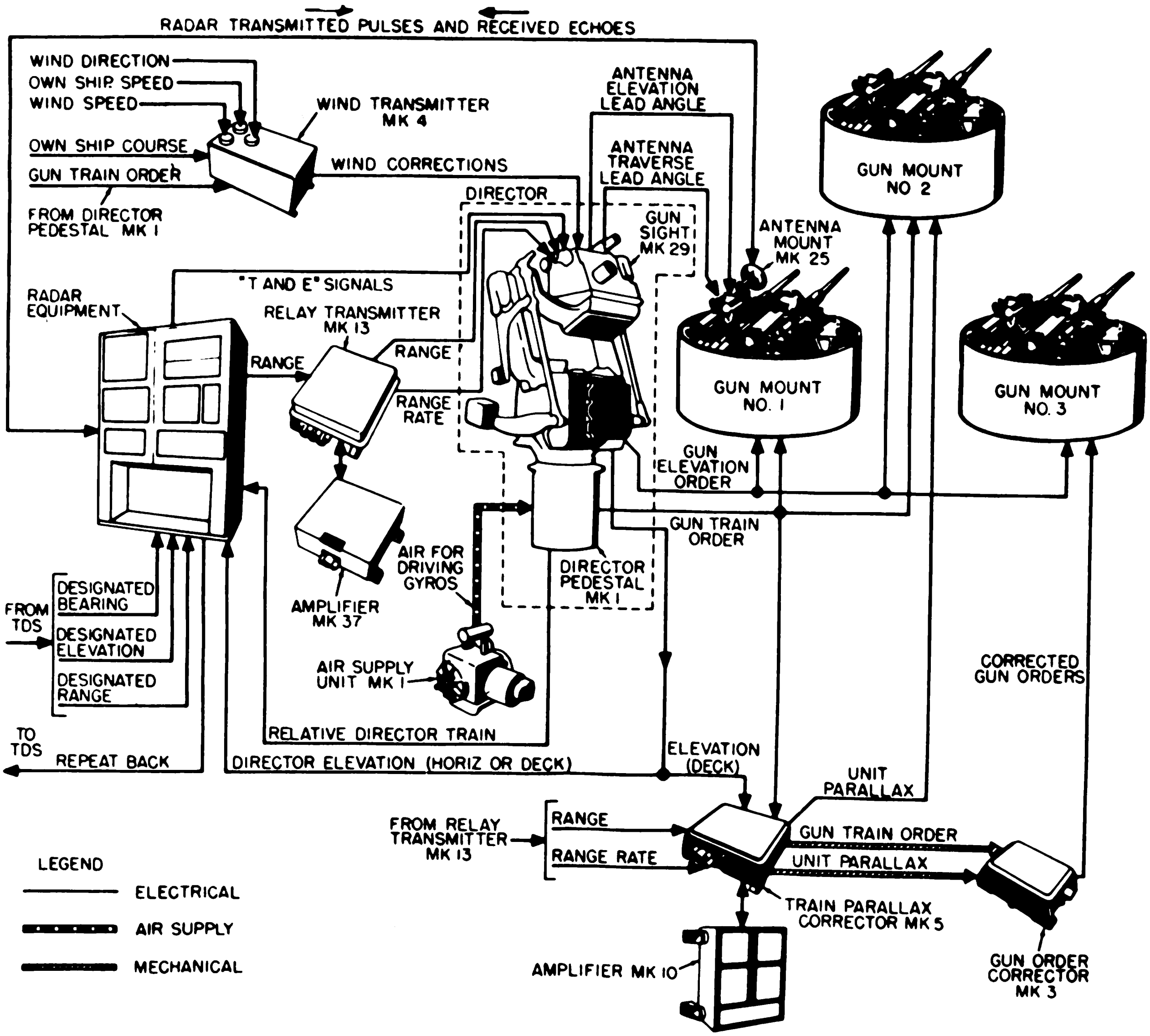

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Figure 10-29.—Gunfire Control System Mk 63 data flow.

tracking blind, train and elevation information from the radar. The gunsight transmits an electrical signal equal to the lead angle which is used to keep the radar antenna in the line of sight.

The amplifier console (not shown) contains seven servoamplifier channels to amplify the following signals: range, range rate (between relay transmitter and gunsight), antenna elevation and traverse lead angles (between gunsight and antenna mount), and three cross-roll channels. In addition, the console has one amplifier channel for testing and a test panel to aid in checking the operation of the elements of the director system.

The wind transmitter computes the corrections made necessary by the effect of wind on the projectile, and sends this information to the gunsight. This information is applied to the gyros in the gunsight to generate lead angle corrections.

The air supply unit supplies compressed air to the director head and the gunsight for spinning the traverse, elevation, and cross-roll gyros, and for actuating the gyro caging device.

The relay transmitter uses range signals received from the radar to measure the rate at which target range changes. It sends both range and range rate to the gunsight and parallax corrector. The relay transmitter must be accompanied by the Amplifier Mk 37.

Up to now we have assumed that the director and the associated gun mount were located close to each other. Aboard ship this is not always the case. The distance between the director and the gun mount is called base length. If this base length exceeds 30 feet the gun order must be modified as shown in figure 10-30. In the system only the horizontal base length, measured parallel to the ship's centerline, will exceed 30 feet.

Horizontal parallax is a correction to gun-train order to compensate for the horizontal displacement between director and gun mount. The gun-train order is modified and the mount is trained towards the director ("toed in"). The line of fire established by the lead-computing sight is intersected by the gun's line of fire at the aiming point.

Frequently a director is assigned a secondary gun mount whose base length differs from that of the primary gun mount. To eliminate the necessity for computing more than one horizontal parallax, a constant of 100 yards base length is used. The parallax thus computed is called "unit parallax". The individual base length correction is accomplished by parallax change gears, with different gear ratios. For example, if the base length is 50 yards, a 2:1 stepdown gear ratio would be used to obtain the correct parallax.

The train parallax corrector computes the parallax correction for the fore-and-aft displacement between the director and the gun mount when necessary. The parallax corrector and its associated Amplifier Mk 10 receive electrical data representing gun-train order, range, range rate, and true director elevation, and electrically transmit gun-train order corrected for a particular base length to the associated gun mount. It sends unit parallax and uncorrected gun train order to one or more gun order correctors as mechanical data. Each gun order corrector electrically transmits gun-train order corrected for a different base length to a separate gun. A maximum of three gun order correctors may be connected in series to one parallax corrector.

Some gun mounts have incorporated in their gun-train receivers a mechanism which performs the functions of the gun-order corrector. In this case uncorrected gun-train order and unit parallax are transmitted electrically to the gun mount.

Gun-elevation order is transmitted from the director to the gun mount. There is no correction made to it.

The radar equipment measures target range and determines target position in traverse and elevation. The equipment sends range information to the relay transmitter, which forwards it to the gunsight, and sends traverse and elevation information directly to the gunsight for use in blind tracking. The radar includes a target acquisition system to help the director pointer to pick up designated targets. It compares true director train and elevation with the bearing and elevation of a designated target. Signals from this comparison are sent to the gunsight's cathode-ray tube to guide the director pointer to the designated bearing and elevation.

The radar antenna mount supports the radar antenna on the gun slide, and offsets it from the line of fire during tracking so that the antenna remains on the target. The position of the antenna is controlled by servo signals from an electrohydraulic drive which receives its signal from the gunsight via the amplifier console.

GUNSIGHT ADJUSTMENTS

We are interested here in the reasoning behind the tests and their corrections. The

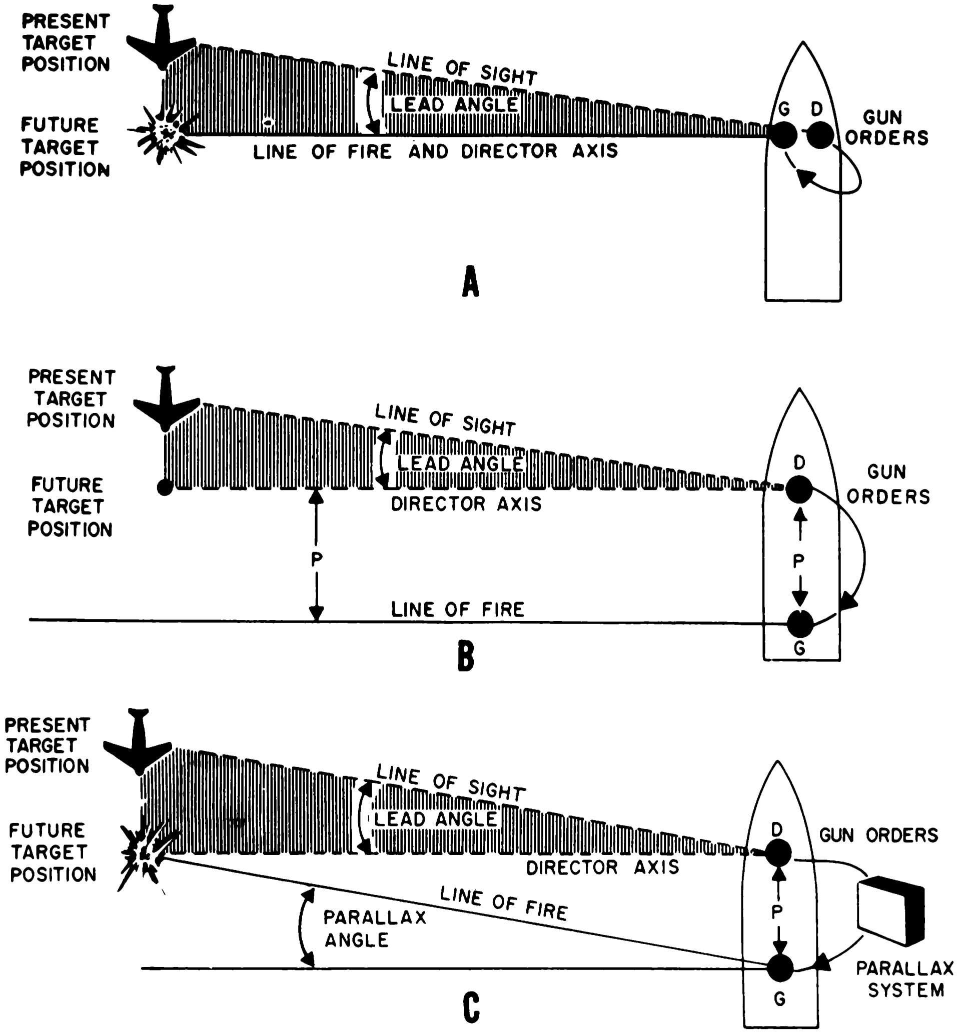

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Figure 10-30.—A. No parallax correction necessary;
B. Parallax correction necessary but not applied;
C. Parallax correction applied.

system OP will describe the method of accomplishing the tests and the corrections which might be necessary. Due to the nature of the angular rate solution the tests are dynamic. To see why this is so, let's see if we can make a concise functional statement of the angular rate solution. The solution is obtained by first establishing a rigid reference line, the line of sight, and then measuring the rate of angular motion of the reference line versus its rigidity. Both steps are performed by the gyros. All the factors in the problem are introduced as torque components in the traverse or the elevation axis of the gyros. The resultant torque in each axis causes the gyro to prescess against the rigidity and the damping of the gyro. The damping can be considered as a restraining torque on the gyro and the rigidity as an inertial torque produced by the gyro. When all the torques are balanced within a system the angle of gyro precession is directly proportional to the lead angle. Since the tests of the sight deal with the generation of the correct lead angle, produced by the balance of the torques, the tests are dynamic.

The tests check the sight's solution of simulated problems against predetermined correct solutions. The tests are run under controlled conditions. The first necessary condition is that the gyro under test has the correct amount of rigidity. This is established by a test of gyro wheel speed.

GYRO WHEEL SPEED

The ability of the gyro to measure an angular rate correctly depends on its gyroscopic properties, which in turn depend on gyro wheel speed. We will use the Gunsight Mk 29 as an example of the test. Each gyro has an individual wheel speed and this information is supplied with the gunsight. The gyro wheel speed is approximately 8300 rpm.

Each gyro has a built-in magnet used to measure wheel speed. With each revolution of the wheel, the magnet passes a winding and induces a voltage. This voltage is amplified and applied to a frequency meter. The meter reads the frequency of the voltage and hence gyro wheel speed.

The gyros in the Mk 29 gunsight are driven by compressed air. If the wheel speed is incorrect, the director's air pressure should be checked at the gage on the director. The gage should indicate in the green area, or 7.5 psi, (pounds per square inch). If it does not, the air pump should be adjusted. Next, the air pressure in the gunsight should be checked. The sight contains an adjustable pressure regulating valve, which reduces the air pressure to 3.5 psi. A pressure gage can be installed in the sight's air system to obtain this measurement. If the reading is not correct the valve is adjusted.

At each gyro, a nozzle directs an air stream onto the gyro wheel. The orifice or opening in the nozzle is adjustable. This adjustment directly controls its gyro's wheel speed.

SIGHT SENSITIVITY TEST

Another method of testing gyro wheel speed in the Mk 29 gunsight is the sight sensitivity test. In this test we have a known lead angle as measured on a test scale mounted on the sight. The director is rotated at an angular rate which will precess the gyro an amount equal to a 200-mil lead angle. To maintain this exact lead angle the director's angular rate of motion must be constant. Thus it will take a definite amount of time to rotate the director through 90° of train or elevation. We time this motion and compare it against a standard time. This is a test of the gyro's sensitivity to angular rate. The sight's sensitivity is dependent on gyro wheel speed.

CHARACTERISTIC TIME TEST

The ability of the gunsight to measure an angular rate, multiply it by prediction time, and generate a correct lead angle, is checked by the characteristic time test. This is in effect a measure of the damping action of the sight mechanisms. The damping governs the amount the gyro will precess when acted on by an external force. In this test we generate a lead angle over 200 mils, as measured by a test scale attached to the gunsight, and time the decay of the lead angle from 200 mils to 74 mils. The decay of the lead angle is opposed by the damping force and is aided by the tension on the range spring representing prediction time. The lead angle should decay in a definite amount of time. If the time is not within the limits specified, the dead zero for that gyro must be determined. The dead zero check will be covered next. The dead space is aplit and a new characteristic time test is made. If this test is not within the specified limits, an adjustment to the damping must be made. The damping action is governed by the temperature of the damping fluid. By adjusting the thermal switch for the damping heater we can increase or decrease the amount of damping. If the characteristic time is too high, the damping action is too strong and the temperature too low; we would therefore adjust the damping thermal switch to increase its temperature.

DEAD ZERO TEST

The dead zero test will determine it an excessive amount of friction exists within the gunsight mechanism. Since we have only a small amount of power available from gyro procession, and it is a direct measure of lead angle, any friction would result in an incorrect lead angle. In this test the reticle is set on a reference line on the test scale by the spotting mirror. The director is slewed in one direction and then slewed back. After the reticle settles, it is brought back to the reference line by the spotting mirror, and a reading is taken of the amount of spotting. This procedure is repeated in the opposite direction. The difference between the two readings is the amount of dead space in the gyro system. This is a measurement of lost motion and friction. The dead zero position is midway between the reference line and the point from which the reticle was spotted when measuring dead zero. This is set by using the spotting mirror. If it exceeds 3 mils, the sight must be returned to a repair base.

OTHER TESTS

It stands to reason that if the testing is to be comprehensive, all the quantities which affect lead angle must be tested. The drift, superelevation, wind, and cross-roll factors, all of which modify the lead angle, enter the problem as torques acting on the gyros. The torques are algebraically added by the gyro and the resultant torque causes the precession which will result in the total lead angle. Thus a test to check the effect of one of these factors should be run only after the tests of the gyroscopic properties have been completed.

Each factor is tested in turn. While one factor is being tested the other factors are placed on zero. Hence the only torque on the gyro during the test is the torque being tested. A percentage of the factor under test is applied as a torque to the gyro. The amount and the direction of gyro precession is observed on the test scale and compared with a standard value.

Although we have referred exclusively to the Mk 29 gunsight, the same type of tests are used to check electrically driven two-degree-of-freedom gyro gunsights. As an example, take the sight sensitivity test to check for gyro wheel speed. Obviously, if the results were unsatisfactory we would check the gyro's prime mover, which in this case is the source of the electrical power. The principles, however, remain the same in either type of sight.

CHAPTER 11

ANALOG COMPUTERS

In chapter 8 we discussed servomechanisms that perform mechanical work for us. In this chapter we will discuss computing mechanisms that do mental work for us. These mechanisms perform the mathematical and logical operations needed to solve the fire control problem. Once the problem has been stated and the method of solution determined, the mathematics in the solution follows steps which are repetitious. For example, in multiplication the relations between the multiplicand, multiplier, and product are laid down by mathematical rules. The logical operations which the computer performs consist mainly of determining the problem's conditions. If the computer is tracking a target which is traveling at high speed and is located above the horizon, the computer will logically assume that the target is an air target, and operate accordingly.

DEFINITION OF A COMPUTER

Computers are instruments that accept information and perform mathematical and logical operations in a systematic order at high speeds. The mathematical operations include summation (addition and subtraction), division, multiplication, vector analysis, and other mathematical manipulations. The logical operations include comparing, selecting, sorting, and matching of input information with information stored in the computer.

Computers may produce answers in either a numerical or a physical form. By physical form we mean voltages or shaft and gear revolutions and positions. The principles here are similar to those we discussed in the chapter on data transmission systems. Because computers can quickly solve interrelated equations simultaneously, they are used to direct gunfire and missiles.

BASIC CONCEPTS

Two chapters in Basic Electronics, NavPers 10087-A, cover the introduction to computers. Before you proceed to study fire control computers, be sure you understand the fundamentals of computers. Fire control computers are indeed complex instruments, and you will find them difficult to master unless you understand the basic concepts. Most fire control computers are special purpose analog computers. We will very briefly review the theory of operation of an analog computer. This review is complementary to the coverage in the basic text.

An analog computer simulates the interrelation of the factors in one system by using a more convenient system. The relations between the factors in any system are established by measurements, and are correlated mathematically. In the basic text the problem dealing with the force acting on a missile was stated by the formula $F=ma$. The problem was solved by substituting an electrical system and its formula $E=IR$ (fig. 11-1). The factors in both systems are defined by a number and a unit of measure. For example, if we say the electrical system has 30 volts, we are saying that there are so many (30), basic units of measure (volts), in the circuit.

Basic units of measure describe the fundamental characteristics of a physical system. In a mechanical system, the basic dimensions to be measured are length, mass, and time. The corresponding basic units of measurement are feet, pounds, and seconds. Other dimensions in a mechanical system can be measured in units derived from the basic units. For example, a force could be measured in foot-pounds per second per second. But this is a rather clumsy unit. For that reason force is often specified in terms of a derivative unit—acceleration—in accordance with the formula $F=ma$, in which

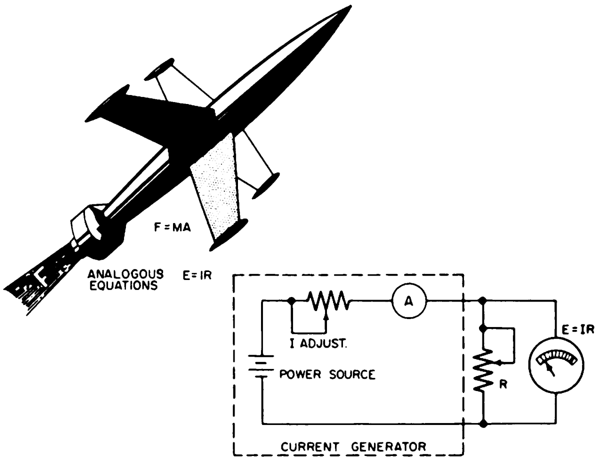

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Figure 11-1.—The analog approach to measurements.

''m'' stands for mass and ''a'' stands for acceleration.

As you well know, the basic dimensions of an electric circuit are electrical potential, current, and resistance; and the corresponding basic units are volts, amperes, and ohms. The relationship between the basic electrical quantities is expressed in the familiar formula E=IR.

Because this relationship is identical in form with F=ma, we can solve the mechanical formula by building a circuit that will solve the electrical formula. For example, we could apply a voltage to the electrical circuit which is proportional to the force acting on a missile. And we could make the circuit resistance proportional to the mass of the missile (using the same scaling factor, of course.) We can then calculate the acceleration of the missile by measuring the current in the circuit, and multiplying by the same scaling factor that we have used throughout the problem.

Of course the example we have given is a very simple one, but it illustrates the basic principle of an electrical analog computer. We can solve any mechanical problem electrically if we can put together an electrical analogy of it—that is, a circuit in which the relationship between electrical quantities is the same as the relationship between the mechanical quantities that they represent.

SHORT HISTORY OF FIRE CONTROL COMPUTERS

This short history of fire control computers will show the important developments from a simple plotting board to the present day fire control computer. In 1910 the first plotting board was issued to the fleet. It was designed to determine range rate. It was important in those days, as it is now, to be able to predict ranges in case there was an interruption in the measurement of ranges. You must know how far it is to a target at all times, if you are going to hit it repeatedly. Today radar sends continuous present target range to the computer. In 1910 the optical rangefinder was the primary means of obtaining ranges. Ranges received from these instruments are intermittent. The plotting board provided a means for plotting successive rangefinder ranges against time, and for drawing through them a smooth line of the range track. By projecting the track ahead, a good estimate was made of target range for any instant. The plotting board provided a graphical solution to the problem of determining correct range to the target independent of the rangefinder for short periods of time. Range, as you read in chapter 2, is the basic measurement in determining the amount a gun must be elevated to cause the projectile to land on or intercept the target. It's interesting to note that the present plotting room got its name from the space aboard ship that housed this instrument. These boards were used as a secondary means of rangekeeping until about 1945.

In 1915, Ford Instrument Company built a mechanical rangekeeper for the U.S. Navy. It contained a number of analog computing elements almost identical with some that you will study in this chapter. As its name implies, it kept the range and produced (generated) a continuous present range. This rangekeeper was the Mk 1. Its successor, called the Baby Ford saw service in the fleet for over 20 years. It computed range rate and bearing rate. The success of these early rangekeepers aroused the Navy's interest in analog computers. Since then the Navy has developed a series of naval fire control computers. In 1924 the first computer and director for the control of gunfire against air targets was introduced to the ships of the Navy. In 1939 the Mk 1 computer was installed in ships as the primary defense against aircraft. The Mk 1 was modified in the late 1940s to increase its effectiveness against high speed air targets and was redesignated the Mk 1A. The 1A has since been modified for use with guided missiles.

World War II brought about some important changes in analog computer design. Prior to the war they were mostly mechanical in design. The development during the war leaned more toward electronics than mechanics because lightness, compactness, and speed can be obtained more easily with electronic components.

Immediately after World War II there were a number of analog computers designed to use vacuum tube amplifiers. These computers also made use of electrical computing elements and mechanical linkages. The most outstanding example of these linkage computers is the Mk 42 computer, which is a component of the Mk 56 gunfire control system.

The success of electrical computing resulted in changes in basic computer design. The weak link in electrical computation has been the vacuum tube. The use of transistors has eliminated this weakness in many applications. Transistors consume less power and they last longer. In addition, some computers use magnetic amplifiers to develop the required power levels. In modern computers, groups of basic elements are packaged into plug-in modules. The modules are isolated mechanically but connected electrically. Accessible test points are provided to allow measurements of the various voltages within the computer. This permits rapid discovery of defective elements. Replacement of a defective module is a simple task.

REQUIREMENTS OF A FIRE CONTROL COMPUTER

The computer includes most of the controlling, computing, and transmitting mechanisms for a fire control system. The instrument is a combined position keeper (range, bearing, and elevation keeper), predictor (which computes the position of the line of fire and time factors for the weapon), and deck-tilt and trunnion-tilt correctors (which provide stabilization for the line of sight and line of fire, respectively.) Supplied with the proper inputs, the computer will provide the necessary data to keep the director on target, and the necessary orders to keep the weapon launcher directed at the aiming point. At the same time, the computer will transmit to other stations and instruments certain data required for their operation.

The destruction of a distant moving target by a weapon whose lethal radius is small, requires a high degree of accuracy. The size and weight of a shipboard computer are necessarily limited. We must therefore do without the accuracy that is inherent in large computers. To obtain the needed accuracy, the smaller basic elements in fire control computers are made to be as accurate as possible.

BASIC COMPUTING ELEMENTS

Your study of the computer should be based on an understanding of the mathematical problems involved, and of the basic computing elements used to solve fire control problems. In some of the preceding chapters, the elements of the fire control problem were presented. In this chapter we will concentrate on the basic computing elements that make up an analog computer. We will show how it is possible to connect some of these elements to form simplified computing networks or loops, and explain their interrelated functions. In a later course in this series we will cover the solution of the fire control problem, and then tie the problem to the computer. Hence your study of analog computers will parallel your study of the fire control problem.

Many computing elements are covered in the basic training courses: mechanical elements in Basic Machines, NavPers 10624-A, and electrical elements in Basic Electronics, NavPers 10087-A. These elements will not be discussed here; we will simply refer you to the basic text. Remember that the computing methods and elements presented here and in the basic courses are basic; you will find many variations of these methods in the actual equipment. Fundamentally, however, computing elements that perform the same function operate in a similar manner.

For our purpose here we can divide the computing devices into two major groups according to the kind of mathematical operations they perform—LINEAR and NONLINEAR. We can further group the computing devices by the method they use to solve the problem—ELECTRICAL, using voltages and current; ELECTROMECHANICAL, using voltages and shaft positions; and MECHANICAL, using angular rotations of shafts, and linear movement of shafts and linkages.

LINEAR FUNCTIONS

A linear function in mathematics is one that can be shown by straight lines on a graph.

Linear functions include summation (addition and subtraction), multiplication, and division, but not squares, square roots, trigonometric functions, and the like. This is covered in the course Mathematics, NavPers 10069-B. Be sure you are familiar with the mathematical problem being solved before you try to understand the mechanization of the problem.

Summation

The process of summation can be accomplished with electrical, mechanical, and electromechanical devices. Voltages are added, motions are added, or voltages and motions may be combined to give an output proportional to the inputs.

ELECTRICAL SUMMATION.—Electrical summation circuits are covered in Basic Electronics, NavPers 10087-A. Therefore we will not discuss their basic theory here. Although a summing circuit's output can be considered as a summation of analog voltages, the real job of the circuit is to determine the algebraic sum of computer variables. These variables are represented by the analog voltages. Therefore a scale factor is assigned to each voltage. In figure 11-2, the scale factor has been changed by the parallel resistance summing network from 1v = 10 ft to 1v = 20 ft or by a ratio of 1:2. If a third signal voltage were introduced through an additional parallel leg, the scale factor would again be changed. The change would be determined by the ratio of the resistance in the legs. Since the voltages represent quantities, the circuit must be extremely accurate, and the scale factor must be considered.

SUMMING NETWORK BOX.—Parallel resistor summation circuits are sometimes contained in plug-in modules called network boxes. The network box contains precision wire-wound resistors. As you can see in figure 11-3, capacitors are connected in parallel with the resistors to compensate for inductance in the resistor windings. The capacitors are not normally shown in circuit diagrams of network boxes.

A network box used by itself is not very accurate for the summation of analog voltages. Among its drawbacks

1. The input signals are highly attenuated in the circuit.
2. The parallel legs interact with one another.
3. Because of high output impedance, a change in the output load will produce a scaling error.

The addition of a feedback amplifier in the summing loop will prevent loading, and thus permit summation of voltages without a scale change. The amplifier (fig. 11-4) is a plug-in module; it provides negative feedback to the network box. The output of the network box, eg, is the signal input to the amplifier, the output of the amplifier -Ef, is impressed across the feedback resistor Rf. Hence eg is equal to the sum of the input voltages that we want to add, +E1 and +E2, minus the feedback voltage Ef. Therefore when -Ef is equal and opposite to the sum of E1 and E2, the signal voltage to the amplifier will be nulled. In this condition the output of the summing circuit, Ef, will be equal to the sum of E1 and E2. The amplifier has a high gain to ensure accuracy. The overall loop gain is proportional to the ratio between the feedback resistor and the input resistors. The circuit can be designed to provide summation

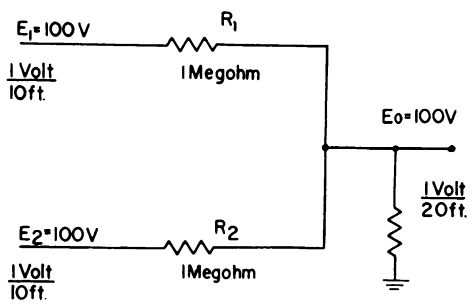

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Figure 11-2.—Scale factors in a summation network.

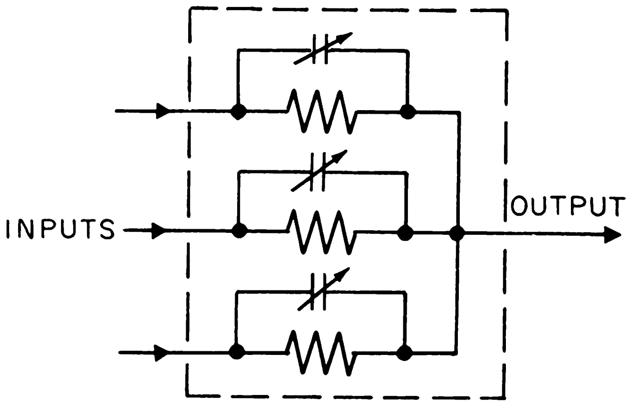

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Figure 11-3.—Parallel resistor network.

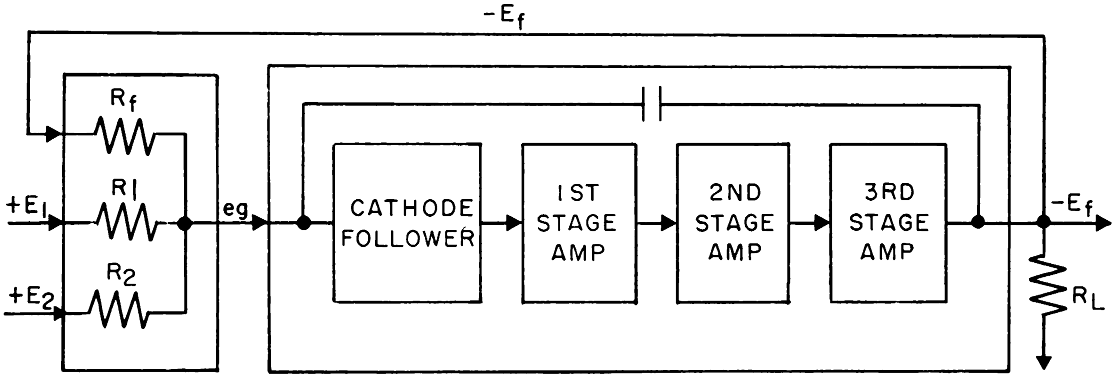

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Figure 11-4.—Network box with a feedback amplifier.

without a scale change, or to provide a scale change when desired.

When more than two electrical signals are to be added, a bigger network box would be used. There are as many legs in the box as there are signals to be added, plus an answer or feedback leg. In some network boxes there are as many as 11 legs.

Does the feedback principle look familiar to you? It should, for it's the same principle we discussed under servomechanisms.

A feedback amplifier can be used to reverse the sign of a signal voltage without changing its magnitude (fig. 11-5). Amplifiers are also used to isolate one computing element from another, as well as to eliminate loading. Because of the various functions this type of amplifier can perform, it is called by several different names: feedback, computing, summation, operational, buffer, or isolation amplifier.

ELECTROMECHANICAL SUMMATION.—Electromechanical summation can be accomplished by a synchro differential system. The principles of this type system are covered in Basic Electricity, NavPers 10086-A.

MECHANICAL SUMMATION.—Mechanical summation devices are of two basic types—those that use rotary gearing in an arrangement called a differential, and those that use linkages with linear movement. Differentials are divided into types by the gearing they use: bevel, spur, and planetary. The bevel gear differential is by far the most common, but fundamentally all three types operate in the same way. Differentials and linkages are covered in Basic Machines, NavPers 10624-A.

Multiplication

Multiplication is another of the linear mathematical operations which must be performed

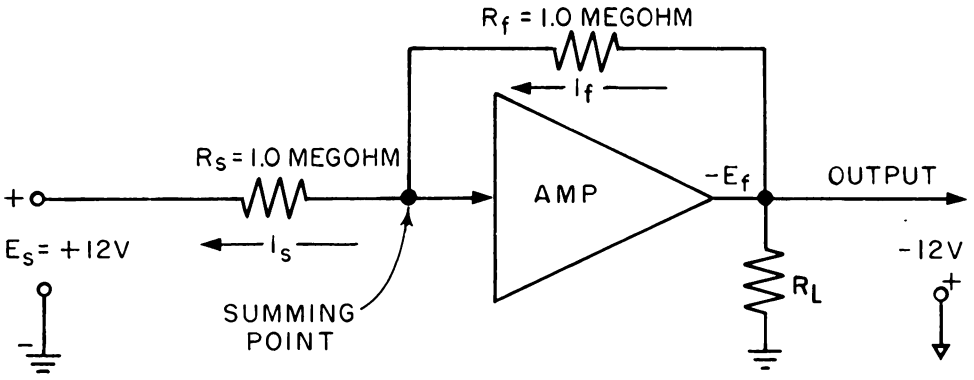

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Figure 11-5.—Sign reversing loop with unity gain.

by a computer. It may be performed electrically by electron tube amplifiers, electromechanically by potentiometers, or mechanically by devices called multipliers.

ELECTRICAL MULTIPLICATION.—A variety of multiplying circuits have been devised employing electronic amplifiers. However, every linear amplifier is a multiplier. It solves the equation

$$e_o = \mu e_g$$

which is identical to

$$y - Kx$$

The grid signal e_g is multiplied by the tube amplification μ to give the product e_o. A typical amplifier as shown in figure 11-6 may be used for this purpose.

The available output voltage depends on the relation between the tube's internal impedance, r_p, and the load resistance, R_L. Where R_L is large compared with r_p; this equation gives a good approximation of the output voltage.

Theoretically, the input signal voltage would be amplified by the same factor under all conditions. However, the transconductance, amplification factor, and plate resistance of the tube will vary with the applied voltage, and hence cause the circuit amplification to vary with the supply voltage. Therefore computing amplifiers frequently employ negative feedback. Utilizing sufficient negative feedback and a high gain amplifier allows the actual gain of the circuit to be practically a function of feedback and almost independent of circuit variations. Feedback in amplifiers is discussed in detail in Basic Electronics, NavPers 10087-A.

ELECTROMECHANICAL MULTIPLICATION.—Precision potentiometers and variable autotransformers are used for multiplication in computing networks. In electromechanical devices one of the quantities to be multiplied is represented by an analog voltage while the other quantity is represented by a mechanical position. Both of the quantities may be variable. The mechanical input is normally driven by a servosystem. The output of the device is a voltage which is proportional to the product of the input quantities. For our discussion we will consider the devices to be perfect. In a later text we will examine in detail the characteristics of potentiometers.

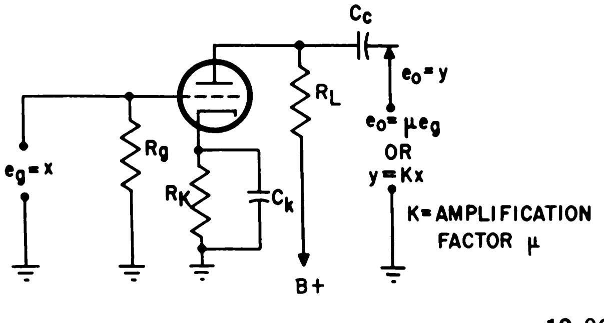

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Figure 11-6.—Typical amplifier as a multiplier.

ELECTROMECHANICAL MULTIPLICATION.—Some of the electromechanical devices used for multiplication are potentiometers, synchros, and precision variable autotransformers. (Usually called by the trade name Variac.)

PRECISION POTENTIOMETERS are frequently used as multipliers in fire control equipment because they are accurate, rugged, simply constructed, and inexpensive. They are equally well suited for a-c or d-c applications. Figure 11-7 illustrates a typical potentiometer type multiplier circuit.

The voltage between the wiper and one end of the potentiometer is the product of two quantities:

$$E_O = E_{in}\theta$$

One quantity is the voltage impressed across the resistor element, and the other is the position of the wiper. When E_{in} is 100 volts and θ is 100 percent, E_O is equal to 100 volts. If θ is 50 percent of full shaft rotation, E_O is equal to 50 volts.

A grounded center tap on the potentiometer winding permits either positive or negative output, depending upon the polarity of the input voltage and the position of the wiper shaft. The primary disadvantage of the

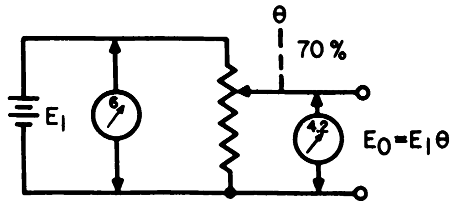

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Figure 11-7.—Potentiometer type multiplier circuit.

potentiometer type multiplier is that a quantity cannot be multiplied by a factor greater than one.

AUTOTRANSFORMER multiplication is similar to potentiometer multiplication except that the input voltage must be a-c. The input impedance of an autotransformer is high, and its regulation under load variations is very good due to the low d-c resistance of the winding.

The low output impedance of the variable autotransformer permits it to be connected directly to other transformers, potentiometers or inductive resolvers, without intervening isolation (buffer) amplifiers.

MECHANICAL MULTIPLIERS.—There are two basic types of mechanical multipliers—those using rotary gears and those using linkages. There are four types of rotary gearing multipliers in fire control equipment—screw, rack, sector, and cam. They all operate in fundamentally the same manner and produce a solution by establishing a relation between corresponding parts of similar triangles.

There are two general types of linkage multipliers used in fire control equipment. One type multiplies a variable quantity by a constant. Its function is similar to that of a gear ratio which changes the value per revolution of a shaft line (shaft value) in a computer which uses rotary gearing. The lever and bellcrank multipliers are of this type.

Linkage multipliers work on the same principles as the simple lever. The formula for a lever is: the mechanical advantage, (MA), is equal to "distance in" divided by "distance out" or MA times distance out equals distance in. The formula indicates that the lever is a multiplication device. In the lever and bellcrank multipliers MA is constant.

The other general type of linkage multiplier is used to multiply two variable quantities. The output of this multiplier is directly proportional to the product of two inputs. One input varies the "MA" in the lever formula. Our primary interest in MA is that the output movement is directly proportional to it. The other variable is the "distance in" or the movement of the input link.

Mechanical multipliers are covered in Basic Machines, NavPers 10624-A.

Division

Division problems are generally difficult for a computer to perform. Multiplication is the inverse of division. When possible, the problem is rearranged so that it becomes a problem in multiplication.

ELECTROMECHANICAL DIVISION.—A rheostat in a voltage divider circuit provides a simple method for dividing a voltage by a shaft position. Figure 11-8 illustrates the operation of a divider circuit.

There are two inputs to the circuit. The first input is the voltage applied to the rheostat which can be either negative or positive. This voltage represents the quantity to be divided. The second input is the mechanical movement of the rheostat contact, the position of which represents the dividing quantity.

The shaft position of the movable contact controls the amount of resistance in series with the fixed resistor. Therefore the amount of voltage applied to the fixed resistor is determined by the angle θ of the contact and the voltage input (E_{in}). Another way to say this is that the current in the fixed resistor is proportional to the voltage in the circuit divided by the amount of resistance in series with it.

Ohm's law states $I = \frac{E}{R}$. We can obtain our answer as a voltage because the voltage is directly proportional to the current—$E - IR$. As in any analog system of division, the divisor cannot go to zero since the quotient would then become infinity. R_2 limits the current, and its value establishes the range of the divisor.

SERVOMECHANISMS are often used for division in computers. Division is usually represented by the equation

$$x = \frac{y}{z}$$

However, in order to use a servomechanism, the equation is rearranged as

$$y = xz$$

hence: $y = xz = 0$

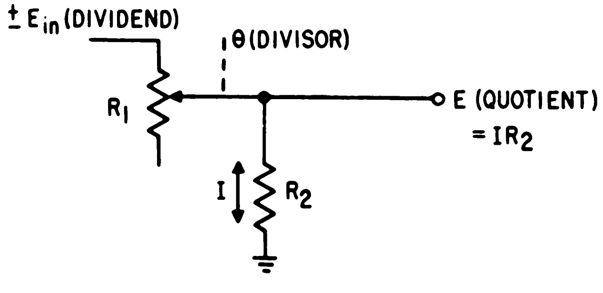

Figure 11-8.—Rheostat divider network.

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The instrumentation of this equation is shown in figure 11-9. The system has two devices which we have already covered. The error detector is an electrical summation device (in this case a resistor network), and the servomotor output applied to the potentiometer is a multiplication device.

In the error detector the input voltage, representing quantity y, is algebraically added to a voltage representing the product of the quantities xz, z being the other voltage input and x the mechanical output which also positions the contact arm of the multiplying potentiometer. The output of the error detector is the voltage difference between y voltage and xz voltage, and is used as an input signal voltage to the amplifier. The amplified signal voltage is used to drive the servomotor in such a direction as to cancel the signal voltage. When y - xz = 0 the servomotor stops driving and the mathematical equation x = y is satisfied.

NONLINEAR FUNCTIONS

In this section we will discuss the instrumentation of such mathematical operations as raising a term to a power, extracting the root of a term, multiplying and dividing by the use of logarithms, and generating trigometric functions. Mathematically, these operations are quite advanced. This, however, is not a course in mathematics. All of these operations are covered in Mathematics, Vol. 1, NavPers 10069-B. Here we are interested only in the statement of a particular problem—not how the statement is arrived at. This greatly simplifies our coverage of the mathematics behind the computing devices. The ideas behind mathematical operations are often simple. Thus if we say a quantity is raised to a power we simply say that the quantity is multiplied by itself a given number of times. The reason for raising a term to a power does not concern us here.

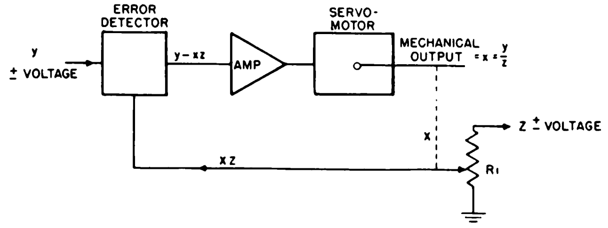

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Figure 11-9.—Division with a servomechanism.

Most of the nonlinear operations can be performed by electrical, electromechanical, and mechanical devices. Frequently these operations are performed by special applications of the linear devices we have previously discussed. For example, a term may be raised to the second power by multiplying it by itself in a multiplier.

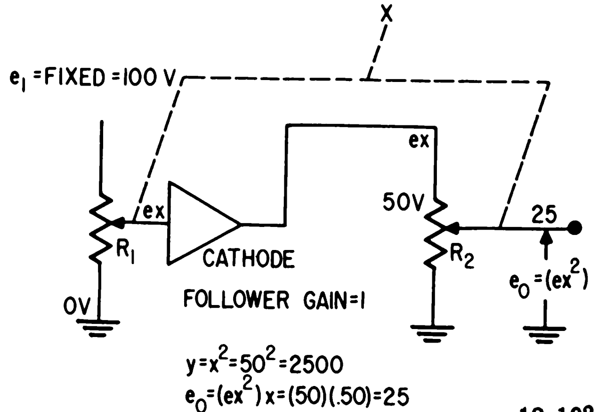
Powers and Roots

A variety of methods are used in fire control equipment for solving problems involving powers and roots. The most common method utilizes electromechanical principles.

POWERS.—The solution of the fire control problem requires use of devices capable of raising terms to a power. In most cases, the term is raised to the second power (squared).

A common ELECTROMECHANICAL method of raising a term to a power is by successive multiplication with potentiometer multipliers. Potentiometer type multipliers have been discussed previously and will not be reviewed here.

The circuit shown in figure 11-10 will produce the square of X, the input quantity. The fixed voltage input to R1 is equal to the unity value of X. In other words, this voltage establishes the scale factor for the circuit. The mechanical input to the wiper arms of the ganged potentiometers R1 and R2 is equal to the value of X we wish to square. The output from the wiper arm of R1 is therefore proportional to X as a voltage. The voltage is fed through an isolation amplifier, which has a gain of unity, to the second potentiometer R2. Here the voltage is again multiplied by the factor X;



12.102
Figure 11-10.—Powers by successive multiplication.

and the output voltage on the wiper arm of R2 is proportional to X times X, or X^2. The variable X may be raised to the third power, and so by adding additional ganged potentionmeters. The power to which a quantity can be raised is limited, however, by the practical limits of voltage available to R1.

ROOTS.—The root of a term may be extracted by either electromechanical or electronic devices. In fact, any multiplying or integrating device capable of raising a term to a power and also capable of producing inverse functions can be used to produce roots. However, in fire control equipment the extracting of roots is normally accomplished by electromechanical devices. A typical device of this type is shown in figure 11-11.

An ELECTROMECHANICAL device for extracting the root of a term or number is a servomechanism feedback loop that uses ganged potentiometers, as shown in figure 11-11. The equation $y = \sqrt[n]{x}$ may be written as $x = y^n$ 0 by raising both sides to the nth power and transposing the y term. Now the term is in required form for servomechanism instrumentation.

Problems in square root may be solved by multiplying the output quantity y by itself and using this value as the feedback term. The output of the square root device is in the form of a shaft position, y.

TRIGONOMETRIC FUNCTIONS

Trigonometric processes can be carried out with inductive resolvers, potentiometers, or mechanical devices. Electronic networks consisting of R and C are sometimes used to perform some trigonometric functions, such as vector addition.

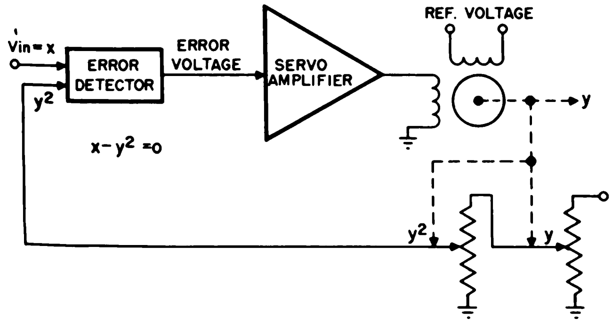


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Figure 11-11.—Square root servomechanism.

Electromechanical Devices

INDUCTIVE RESOLVER.—The inductive resolver is an electromechanical device used to generate trigonometric functions. The inputs to the resolver are (1) the magnitude of the value expressed as a voltage, and (2) its direction expressed as a mechanical rotation. Since the value has both magnitude and direction, it can be represented as a vector. The resolver is basically a right triangle solver, using windings to represent the sides and magnetic flux to represent the hypotenuse. The shaft rotation corresponds to one of the acute angles of the right triangle.

The rotor windings shown in figure 11-12 are two windings 90° apart. Each winding has the same number of turns. The 90° displacement prevents any magnetic coupling between the two windings. The stator windings are wound in the same manner as the rotor windings. The illustration is a schematic representation. However, many times one of the windings is inactive and not shown.

The inductive resolver operates on the principles of a transformer. The two stator windings act as primaries and the two rotor windings as secondaries. The rotor windings turn with the rotor shaft, figure 11-13. Thus,

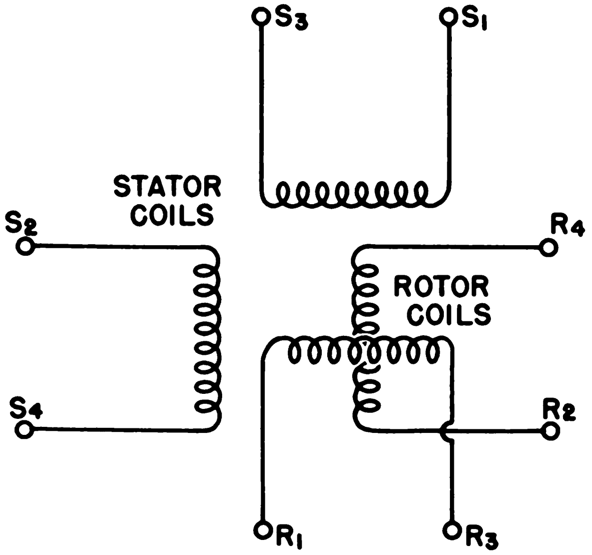

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Figure 11-12.—Resolver schematic.

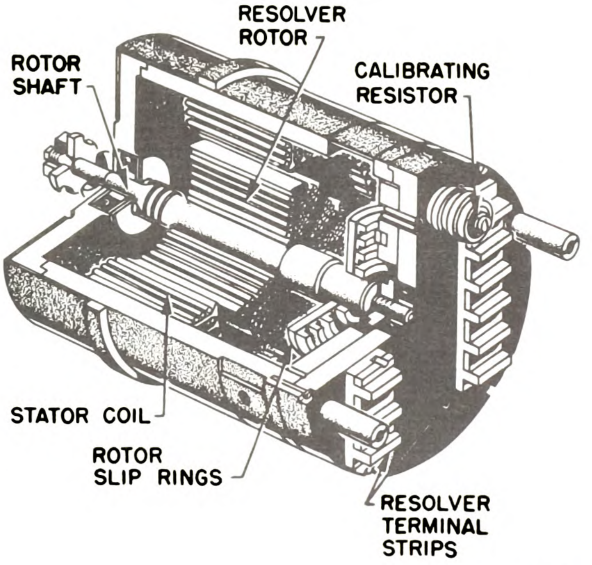

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Figure 11-13.—Cutaway of transformer resolver.

the secondaries may be set at any angle with respect to the primaries. Figure 11-14 shows the rotor in three different positions with respect to the stator. Since similar action takes place in all windings, only one set is shown for simplicity.

In figure 11-14A, the rotor and stator windings have an angle of 0° between them. With the rotor in this position, all the flux established by the stator winding voltage cuts the rotor winding and the voltage induced in the rotor is maximum. For example, with a turns ratio between the stator and rotor of 1:1 and an input voltage of 1 volt, ignoring the small transformer losses, the output voltage will be 1 volt.

In figure 11-14B, the rotor is turned so that the two windings are displaced by 30 degrees. Now only a part of the stator flux cuts the rotor winding, and the voltage induced in the rotor is 0.866 volts.

In figure 11-14C, the rotor is turned so that the two windings are displaced by 90 degrees. At this angle there is no magnetic coupling between the windings, and the output voltage is zero.

The output voltage corresponds numerically to the cosine function of the angular displacement between the rotor and stator. This rotor winding is therefore called the cosine winding. With the second rotor winding displaced 90° from the cosine winding, the voltage induced in this winding would correspond to the sine function of the angle of displacement between the rotor and the stator. This naturally would be called the sine winding.

Here are some of the types of problems a resolver is capable of solving. First, the resolver can separate a vector into its two right-angle components; this is called resolution. The hypotenuse of the triangle in figure 11-15 is the vector to be resolved. The angle A represents the direction of the vector; and the voltage applied to the stator winding, given a value of unity, represents the magnitude of the vector. The output voltages, E_{01} and E_{02}, are the answer to the vector problem. The magnitude of E_{01} represents the horizontal component and E_{02} the vertical component of the vector.

In figure 11-16 values have been assigned to the inouts. The angle of 30° represents the

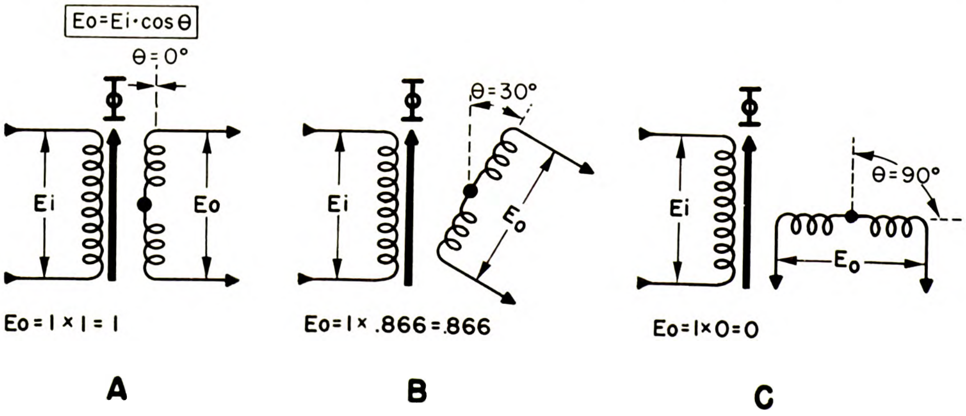

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Figure 11-14.—Resolver principle, rotor and stator.

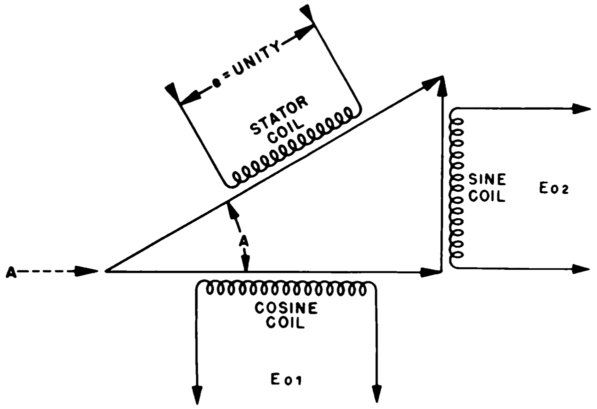

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Figure 11-15.—Resolution #1.

elevation of a target. The hypotenuse represents the range to the target in the slant plane. In this case unity voltage represents the maximum range of the instrument. The voltage applied to the stator is directly proportional to the target's range. The voltage induced in the cosine winding would represent the horizontal range to the target, while the voltage induced in the sine winding would represent the vertical component of the target's range—that is, its height.

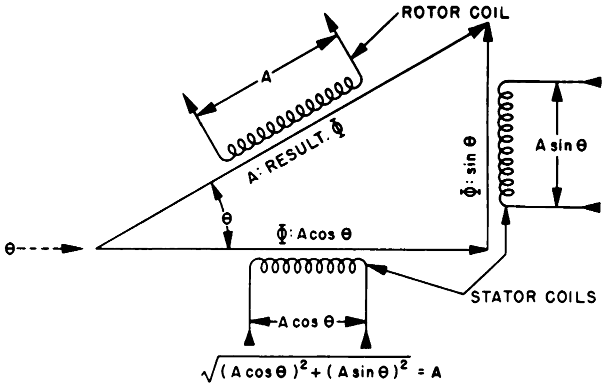

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Figure 11-17.—Composition.

Combining the two components of a vector to produce that vector is the second type of problem a resolver can solve. This is called composition. Here two sides of a right triangle are known and the resolver solves for the hypotenuse. The voltages A sin θ and A cos θ are applied to the two stator windings, as shown in figure 11-17. Each winding produces a flux field proportional to the strength of its voltage. These two flux fields are at right angles because the stator windings are at right angles. Right angle flux fields combine according to the formula

$$\phi_1^2 + \phi_2^2 = \phi_t^2$$

where ϕ_1 is the field strength of stator winding 1 and ϕ_2 is the field strength of stator winding 2. (This formula is similar to the formula used to solve for the hypotenuse of a right triangle—the square of the hypotenuse is equal to the sum of the squares of the other two sides.)

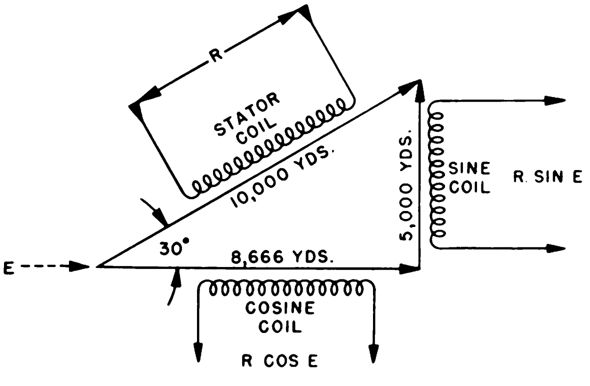

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Figure 11-16.—Resolution #2.

The rotor is turned through the angle θ so that the axis of the rotor winding is aligned with the axis of the resultant stator flux field. The voltage induced in the rotor winding is then proportional to the hypotenuse, which is the vector A.

In a computer, the second rotor winding of the resolver is used to furnish a signal to a servomechanism to position the rotor. The second rotor winding would have zero voltage induced when it is exactly 90° from the resultant flux field. Therefore the rotor would remain in this position and the first rotor winding would have maximum voltage induced.

By the use of more than one resolver in a computing circuit, a combination of the two basic problems can be solved simultaneously.

Zeroing a Resolver.—There are many methods used to zero resolvers. Each manufacturer has his own method. The method described below uses the basic principles underlying all the different resolver zeroing methods.

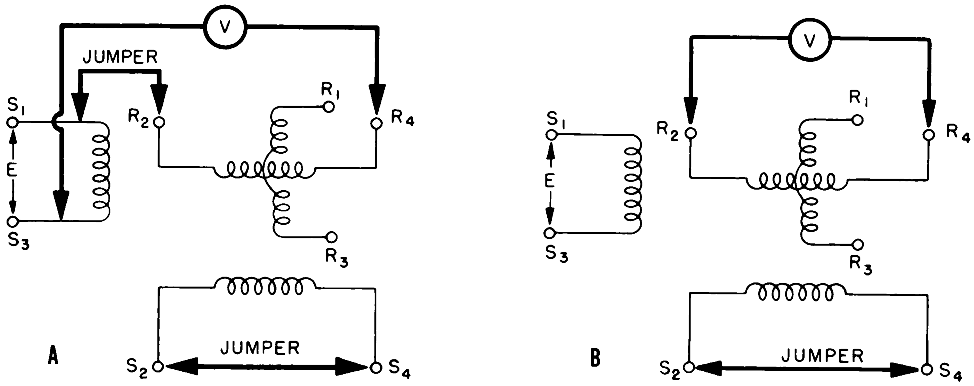
Before a resolver can solve a problem it must have a reference position from which the input values are measured. This is the zero position of the resolver. The zero position of a resolver is determined by the angular relationship between the rotor and stator windings. Each stator winding must be perpendicular to a corresponding rotor winding. When this relationship is established, there will be no magnetic coupling between corresponding windings.

The absence of a magnetic coupling between corresponding rotor and stator windings is possible at two positions 180° apart. To ensure the correct position, so that the phase relationship between the rotor and stator is correct, the coarse zero test is made first. Figure 11-18A shows the connections for the coarse zero test. The voltage applied to the stator winding S_1-S_3 is a reference voltage specified for the resolver. The two windings are connected in parallel by the voltmeter and the jumper. The voltmeter—either a CRO or a VTVM—will read the applied voltage, plus or minus any voltage induced in the rotor winding. The jumper across the winding S_2-S_4 is to eliminate any stray voltage that might originate from that winding.

The voltage at the voltmeter should INCREASE ABOVE E, because the voltage induced in the R_2-R_4 coils adds to E. Be sure the voltage at the voltmeter increases to prevent zeroing at 180° out of phase.

The next step is to set the resolver on fine zero. Figure 11-18B shows you how to reconnect the jumper and voltmeter. Turn the stator so that the voltage on the voltmeter decreases, and keep shifting the meter to the lower scales until the minimum voltage reading is obtained. The minimum voltage reading means that R_2-R_4 is exactly at right angles to S_1-S_2, and the rotor is at fine zero. Recheck this voltage after you secure the mounting screws.

TRIGONOMETRIC FUNCTION POTENTIOMETERS.—A linear potentiometer (pot) has an even distribution of resistance along its entire length. The resultant output varies in even steps with each degree of rotation of the contact arm. As an example, the travel through one-half the arc of a linear potentiometer results in one-half the total resistance between either end and the contact arm.



12.111

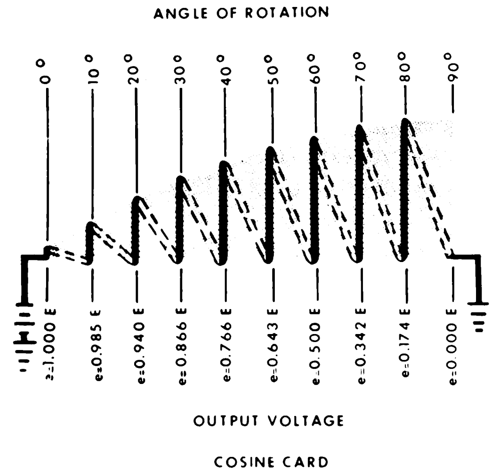
Figure 11-18.—A. Coarse zero; B. Fine zero.

To make the coarse zero adjustment, loosen the flange mounting screws of the stator. Looking at the rear (brush end), turn the stator counterclockwise. Stop turning when the voltmeter reads the input voltage, E. At this point you know the R_2-R_4 coil has no induced voltage because the voltmeter reads the input voltage alone. This means that the R_2-R_4 is approximately at right angles to S_1-S_3, and the rotor is at coarse zero.

With the voltmeter reading the E voltage, turn the stator a little beyond coarse zero.

But all potentiometers do not have a straight line or linear relationship between the amount of contact rotation and the resultant output. A potentionmeter with more resistance per unit length at one portion than at another would be classed as a tapered or nonlinear potentiometer. The travel through one-half the arc of a nonlinear potentiometer may result in one-tenth (or any fraction) of the total resistance between one end and the contact arm.

Figure 11-19 shows a nonlinear potentiometer. The shape of the potentiometer card,



12.112

Figure 11-19.—Cosine card.

and therefore the amount of resistance, is designed to give a voltage output proportional to the cosine of the angle of rotation of the contact arm. A sine card would be the same, except that it would represent zero degrees at its wide end.

Mechanical Devices

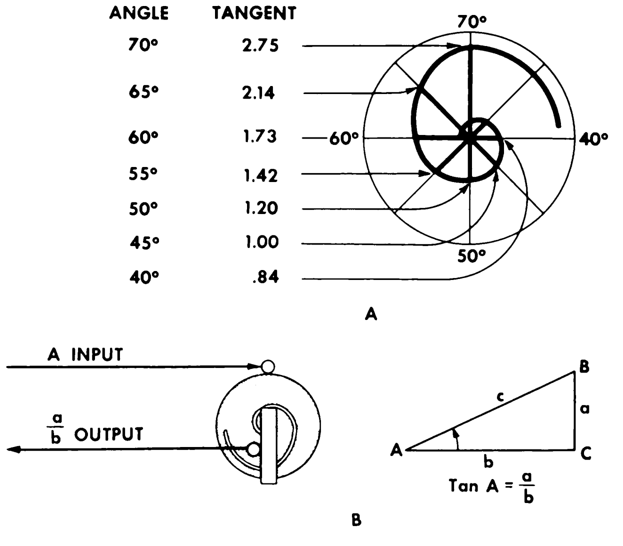
A component solver is a computing device that uses rotary gearing. Its inputs represent a vector of a given magnitude and angular position. The component solver resolves the vector into its two rectangular components. For example, the angular input might be the bearing of the line of sight and the linear input proportional to own ship's speed. The outputs would be proportional to the components of own ship's speed in and across the line of sight.

The angle resolver is a linkage mechanism which computes the sine and cosine functions of an angle. The input angle to the resolver may be target elevation. The outputs would be the sine and cosine of the elevation angle. These quantities are needed to determine target height and horizontal range.

The physical and functional characteristics of the component solver and angle resolver are described in Basic Machines, NavPers 10624-A.

Cams are commonly used devices which produce a mechanical output that has a nonlinear relation with its input. As you know, a cam converts mechanical motion from angular to linear, or vice versa. The output motion is related to the input by the shape or cut of the cam. Thus, dependent on how the cam is cut, the output is some function of the input. Cams in fire control instruments are cut to trigonometric, exponential, reciprocal, and empirical functions.

The tangent and secant cams are commonly used to produce trigonometric functions. Their operation is limited to angles below 90°; this is because the tangent and secant functions of a varying angle approach infinity as the angle approaches 90°. The tangent cam (fig. 11-20) does not differ greatly from the secant cam (or any other cam for that matter), except that the groove is cut differently. Hence a reciprocal cam's groove is cut so that the output is the reciprocal of the input. If the input is equal to R, the cam output movement is proportional to 1/R.

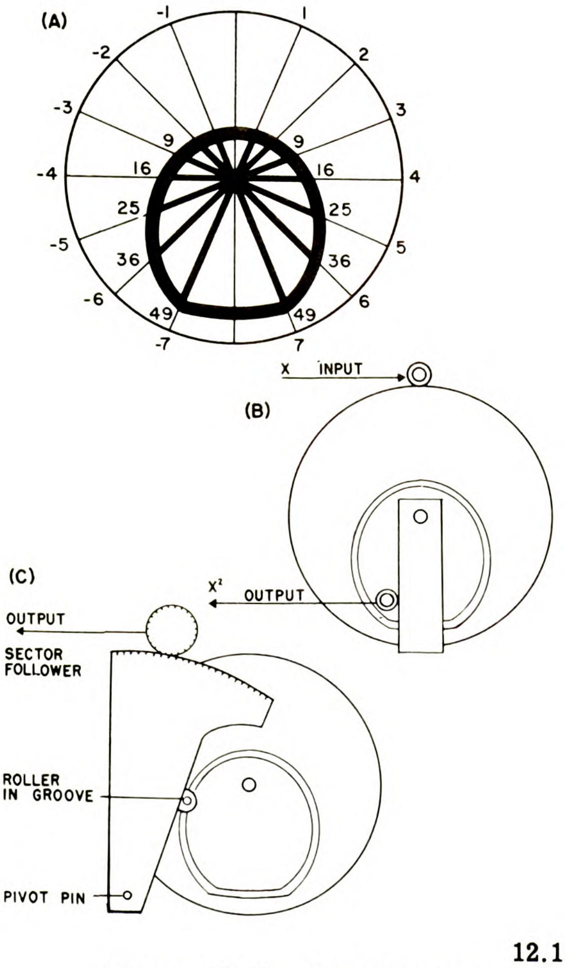


12.116

Figure 11-20.—Tangent cam.

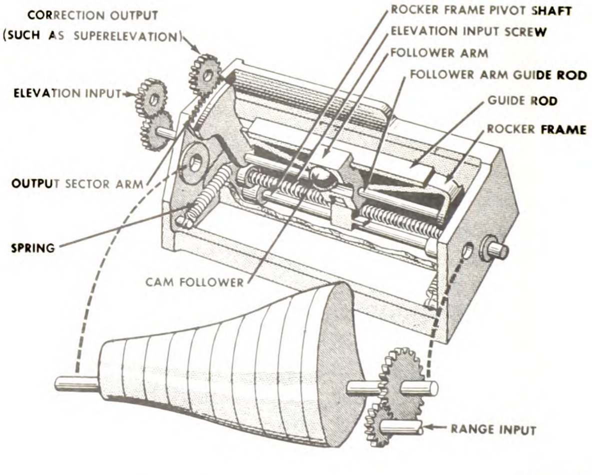
The cam is a MECHANICAL means of raising a term to a power. However, its use is normally limited to squaring a term. Figure 11-21 illustrates a basic square cam and two types of followers used to transmit outputs to other devices. The input positions the cam as indicated by the numbers around the outside of the cam. The follower then registers the output value in accordance with its position in the groove or on the curved surface. The output of a square cam will always be a positive value.

Ballistic cams in the computer are cut to represent empirical functions. An empirical function is one in which the factors cannot be correlated through normal mathematical methods. The function between the related factors is determined by experiments and measurements. Frequently, however, the desired quantity is a function of two factors. In this case a barrel or two-dimensional cam is used. A barrel cam is actually a group of cams consolidated into a single piece (fig. 11-22). In the figure the cam's output is proportional to superelevation, which varies with elevation and range. Elevation drives the cam follower along the guide rod to the correct portion of the cam for that elevation. Range rotates the cam to the correct position. The output is therefore a function of both range and elevation.



12.103

Figure 11-21.—Squaring cam.



12.298

Figure 11-22.—Barrel cam.

COMPUTING WITH LOGARITHMS

The logarithm of any given number is the number of times a second number, called the base, must be multiplied by itself to produce the given number. In the most common system of logarithms, the number 10 is a base. If we multiply 10 repeatedly by itself we get 10, 100, 1,000, etc. These numbers can also be expressed as 10^1, 10^2, 10^3, etc. The logarithm of 10 (to the base 10) is 1, since the base is used only once as a factor to produce that number. The logarithm of 100 is 2, since the base must be used as a factor twice to produce 100. And the logarithm of 1,000 is 3, etc. As you can see, a logarithm is an exponent. Special logarithm tables for various base numbers have been calculated to take advantage of the laws of exponents.

The use of logarithms to solve complicated problems is effective and easy. Multiplying, dividing, and finding roots and powers are some of the operations you can perform quickly and easily with logarithms. The slide rule (which incidentally is a simple mechanical analog computer) is based on logarithms. Logarithm tables, which are included in many mathematics book, can be used for pencil and paper solution of many problems.

Logarithms are covered in Mathematics, Vol. 1, NavPers 10069-B. Here we are primarily concerned with computing devices which use logarithmic processes. In order to understand the operation of these devices it is not necessary to have a complete knowledge of logarithms. The definitions of logarithm and antilogarithm, plus the laws of exponents, will provide you with the necessary background. The definition of a logarithm has already been given. An antilogarithm is the number which corresponds to a logarithm. Hence when you know the logarithm and wish to find the number it is equal to, you use the logarithm tables in reverse. This is called finding the antilogarithm.

As a logarithm represents an exponent, the laws of exponents, which may be a little more familiar to you, can be used to explain logarithmic computing devices. For our explanation we will deal with a specific type of problem. It is simpler and more practical to add or subtract in computers than to multiply or divide. Two laws of exponents will suffice to explain this type of operation. The first law states: To multiply two or more powers having the same base, add the exponents and raise the common base to that power. Thus if we know the logarithms of two quantities we can multiply by a summation process and then find the antilogarithm to obtain the value of the product.

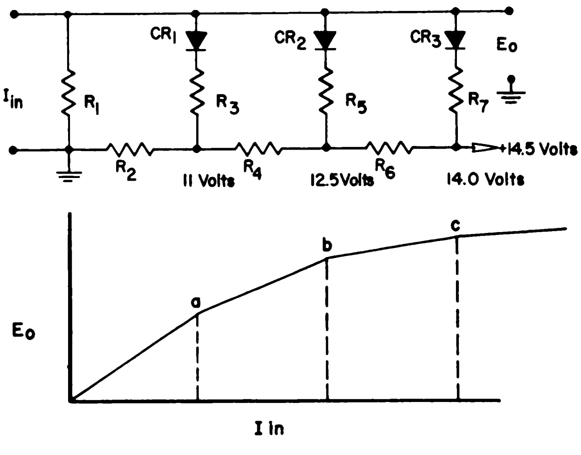
The second law states: For powers of the same base, if the exponent of the dividend is larger, the exponent of the quotient equals the exponent of the dividend minus the exponent of the divisor. If the exponents of the dividend and divisor are equal, the exponent of the quotient is zero and the quotient itself is one. Thus we can perform division by subtraction if the logarithms of the quantities are known.

Logarithm Circuit

Diodes and contact rectifiers under some conditions have nearly exponential variation of current with voltage, or logarithmic variation of voltage with current. However, the operating limits of a single diode are surpassed by the requirements of most fire control computers. This limitation necessitates the use of circuits such as the one shown in figure 11-23 to produce logarithmic functions.

The purpose of this circuit is to produce an output voltage that is proportional to the logarithm of the input current. Referring to figure 11-23, it should be noted that R2, R4, and R6 form a voltage divider network. The cathode of each rectifier is connected through a resistor to some point on the voltage divider. This effectively acts as bias, causing each rectifier to be cut off until its plate reaches a potential higher than its cathode.

As the input current is applied, current will flow up through R1, producing an output voltage proportional to the current (E = IR). As the current, hence the voltage drop across R1, becomes great enough, the positive voltage at the top of R1 will become great enough to bring CR1 into conduction. As soon as CR1 conducts, it effectively places R3 in parallel with R1, lowering the total resistance and producing less voltage drop for a given increase in input current. This accounts for the bend in the curve at point a. The circuit response curve illustrates how the slope is successively reduced as additional rectifiers come into conduction. It should also be noted that an increased number of rectifiers could result in a more perfect curve. However, the circuit shown provides an output from which a curve can be plotted and the circuit operation understood.



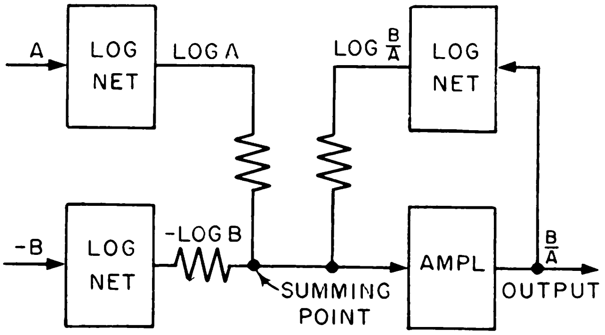
12.299

Figure 11-23.—Typical logarithmic shaping network.

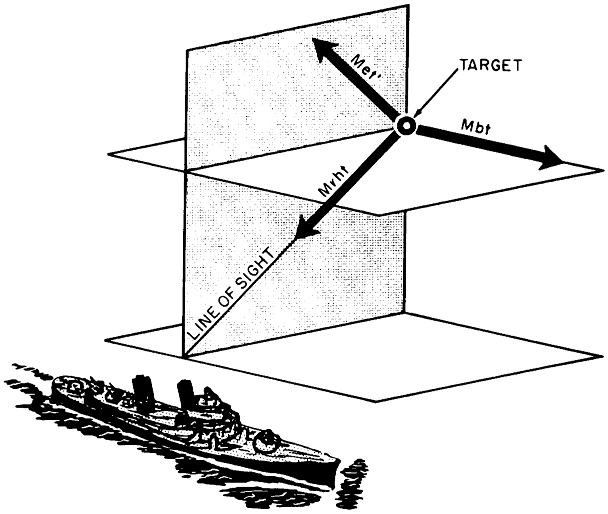
In the network shown in figure 11-24, we are dividing the quantity B by the quantity A. The sign of the quantity B is reversed by a feedback amplifier (not shown). The two factors A and -B are fed into the logarithm networks. The outputs of the networks are the logarithms of the inputs. Since the sign of B has been reversed, the difference of the two logarithms is obtained at the summing point. The difference is the logarithm of $\frac{A}{B}$ according to the second law of exponents. This voltage is fed into the amplifier, which is part of the antilogarithm network. The amplifier inverts the logarithm quotient, so that its output is $\frac{B}{A}$. The output is fed back through the logarithm network to null the signal voltage to the amplifier. The output of the circuit is $\frac{B}{A}$, the quotient of the two input quantities.

RIGHT TRIANGLE SOLVER

A large portion of the fire control problem deals with rates, motions, and displacements in and across a reference line. Consider target motion. It must be resolved into components proportional to the effect it will have on range, bearing, and elevation. Normally a computer first establishes the vector with respect to the reference line, which in this case is the line of sight (fig. 11-25). The computer establishes a right triangle in which the hypotenuse, equal to the vector length, and an angle, equal to target bearing, are known. The computer resolves this vector into its rectangular components in and across the line of sight. The component solver and the angle resolver mechanically resolve a vector into its rectangular components, while the inductive resolver will perform this same job electrically. In applications where some error in the solution can be tolerated, the right triangle problem is solved by using one side and the hypotenuse or the two arms of a right triangle.



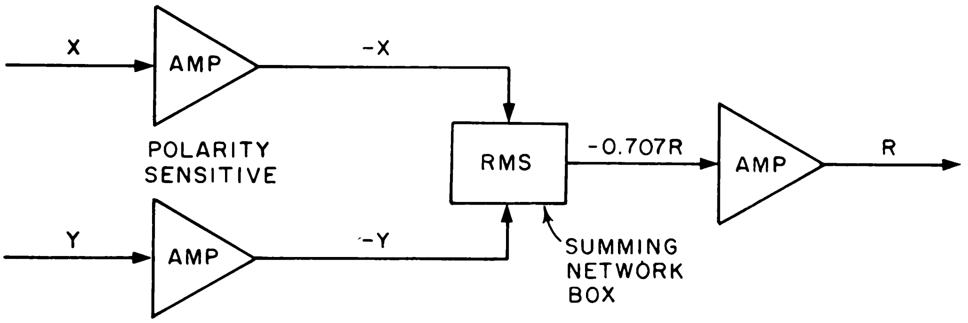
12.300
Figure 11-24.—Division with logarithms.



53.111
Figure 11-25.—Target motion during time of flight.

Two Sides Known

Assume that a computer receives the north/south and east/west rectangular components of the horizontal range to a target. The simplified computing network (fig. 11-26) solves for present range, which is equal to the hypotenuse of the triangle. Range, being a distance from own ship, is always considered positive. But the rectangular components of range, X and Y, can be either negative or positive, depending on which quadrant they are in. Therefore the X and Y components first pass through a polarity sensing circuit, which contains a polarity reversing amplifier. A circuit which bypasses the amplifier is open to a negative signal but closed to a positive signal. A positive signal passes through the amplifier, where its polarity is reversed. Hence the X and Y signal voltages to the summing circuit are always negative. The solution is based on the formula $R^2 = X^2 + Y^2$ or $R = \sqrt{X^2 + Y^2}$. The ratio of the resistors in the RMS network is such that the output is equal to $\frac{X + Y}{2}$. It happens that $\frac{X + Y}{2}$ is approximately equal to $0.707\sqrt{X^2 + Y^2}$.



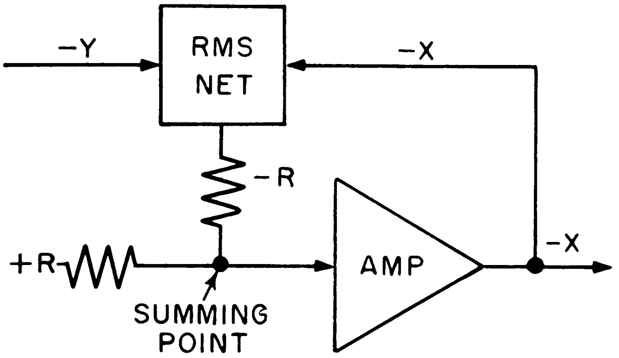
12.301

Figure 11-26.—Right triangle solution—two sides known.

So, for the purpose of this problem, it is sufficiently accurate to say that the output of the resistor network is equal to 0.707 of the hypotenuse R. This voltage is the input to an amplifier whose gain is sufficient to raise the voltage to R. The gain factor of the amplifier therefore would be equal to $\sqrt{2}$.

Hypotenuse and One Side Known

In this problem we know the hypotenuse and one side of a right triangle. See figure 11-27. The voltage that represents the hypotenuse is R. The known side, Y, is the input to the RMS network, and is always negative. The output of the network is equal to -0.707Y. This voltage is summed at the summing point with the positive voltage R. The voltage difference is the input signal to the amplifier. This difference is equal to 0.707 times the length of side X. The gain of the amplifier is high enough to make its output equal to X, the unknown side. The amplifier output is opposite in polarity to its input. The value -X is fed back to the RMS network where it is summed with -Y. Therefore the output of the network is-0.707Y-0.707X, which is almost exactly equal to -R. When this voltage is equal and opposite to the hypotenuse input +R at the summing point, the signal to the amplifier is nulled and the output of the circuit is equal to X, the unknown side.



12.302

Figure 11-27.—Right triangle solution—hypotenuse and one side known.

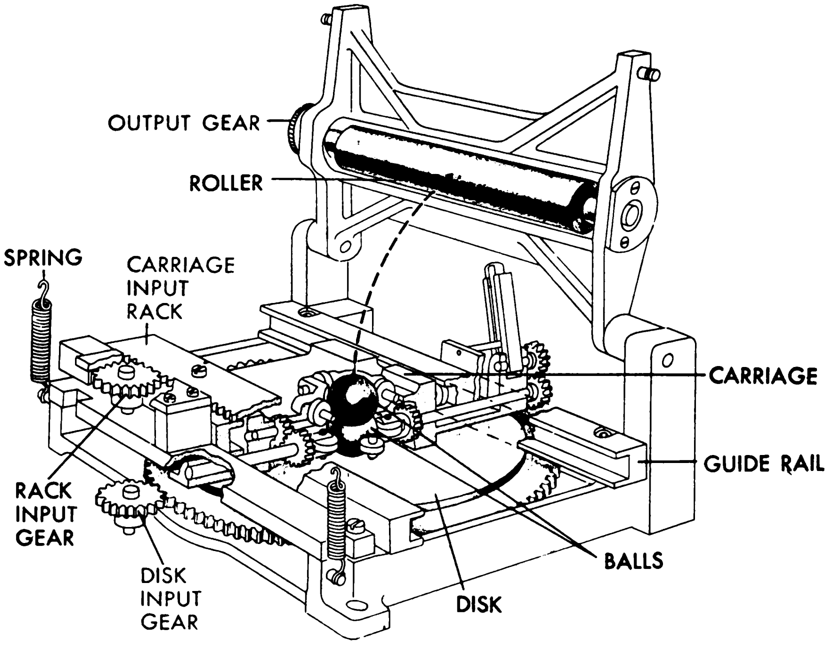
Angular Solution

When an angular value is involved in a right triangle problem, an electromechanical computing network is used. Since many of the quantities in the fire control problem are angles: bearing, elevation, ship and target course, and lead angle to name a few, this type of right angle problem is more frequently encountered than the others. The solution is based on the trigonometric functions of the known or working angle. When an angle and the hypotenuse of the right triangle are known, the sine and cosine functions of the working angle are normally used. Computing elements such as the resolver, potentiometer, cam, component solver, and angle resolver have been covered. The solution to this type of problem was covered when we discussed resolvers. Sometimes the tangent or secant function is used in the solution. Cams and potentiometers are used to produce these functions.

INTEGRATION

The fundamentals of integration and a basic mechanical integrator are discussed in Basic Machines, NavPers 10624-A. Here we will extend the basic concepts of integration and apply the process to the fire control computer.

Integration is the process of determining the change which will occur over a period of time in the value of a variable quantity which is changing at a known rate. Hence integration consists of the summing up of all the minute



12.303

Figure 11-28.—Ball-disk-roller integrator.

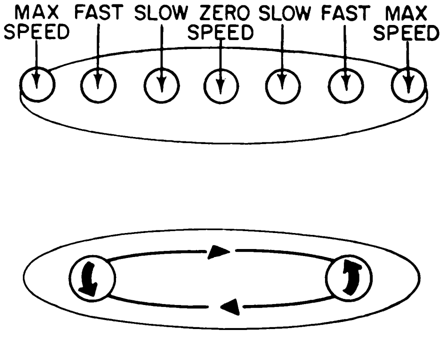
changes in a quantity, to find the total amount of change which took place. Since integration in the solution of the fire control problem is usually the summing of changes in a quantity with respect to time, it is a continuous process.

The change of range for a constant range rate may be computed by multiplying the rate at which range is changing by the length of time of the problem. Hence if the rates in fire control were constant, a simple mechanism would produce the desired output. Under actual conditions, however, the rates vary over a large scale. Therefore a more complicated system must be used.

Mechanical Integrator

The ball-disk-roller type integrator (fig. 11-28) is used in mechanical fire control computers. The integrator disk is mounted on a gear and is turned directly by the input gear. The two balls, one on top of the other, are held in position between the disk and the output roller by the carriage assembly. The carriage is movable, and can position the balls along a straight line from one edge of the disk, through the center, to the other edge. The pressure needed to hold the balls against one another, and against the disk and roller, comes from a spring assembly. The motion of the disk is transferred through the balls to the roller by friction.

The mechanical operation of the integrator can be visualized (fig. 11-29). The circumference of the circle passing under the balls is greater when the balls are near the edge of the disk, and smaller when they are near the center. At the exact center of disk, no motion is transferred to the balls. The balls will turn in one direction when they are on one side of the center of the disk, and in the opposite direction



12.304

Figure 11-29.—Integrator operation.

when they are on the other side. Hence the integrator acts as a reversible, variable gear ratio between the input to the disk and the output from the roller. The ratio is changed by the input to the carriage.

Let's look at a practical application as found in a computer. Since you are familiar with the range integration problem from your study of the basic text, we will use it as an example.

When the target is picked up, the initial range is set into the range system. At that moment, the time motor is turned on, setting the disk in motion. The rotating disk, then, can be compared to a clock which is constantly ticking away the passage of time from the instant the target is first sighted. In the range problem the disk always rotates in the same direction at a constant speed. This is a mechanical way of saying that time, which the disk represents, always goes by and never backs up.

Range rate is fed from the range rate system into the carriage input gear, which positions the carriage and the balls according to this rate. If the range rate is fast, the carriage will locate the balls away from the center near one edge of the disk. If the rate is slow, it will locate them near the center of the disk. The speed of the balls depends on their distance from the center of the disk, so the speed of the balls is always proportional to the range rate.

The output roller is constantly being turned by the balls, with the roller's speed determined by the speed of the balls. The position of the roller at any moment (that is, the number of revolutions it has made from its initial position) tells the actual change in range during the time the disk has been turning. The output roller is geared to the range dial through a differential, so that this change in range is constantly being added to the initial setting to give present range at any moment.

Electrical Integration

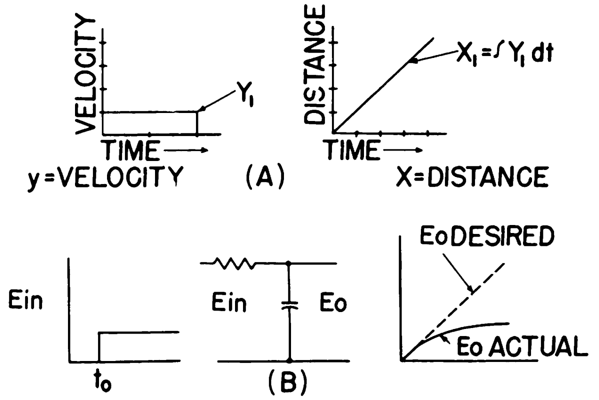
This section deals with the characteristics of resistors and capacitors connected in series. We are interested in the variations in voltages produced across each of them during a given time period, and their use in computer circuits as differentiating and integrating devices. As you know from your study of basic electronics, when the output of an RC circuit is taken across the resistor the circuit will perform differentiation, and when the output is taken across the capacitor the circuit will perform integration. The differentiating circuit produces an output voltage that is proportional to the rate of change of the input voltage, while an integrating circuit produces an output voltage that is proportional to the accumulation of the input voltages to the capacitor. The time period during which this occurs is determined by the RC time constant of the circuit. We will first consider integrating circuits.

INTEGRATION

Integration is the process of summing up an infinite number of minute quantities. However, in the solution of the fire control problem, integration is usually the summing of certain quantities in respect to time. For example, taking the integral of velocity between certain limits of time will give the distance traveled.

The process of integration is analogous to determining the area under a curve. In the case of a step function input, the "curve" may be considered as a rectangle having one side variable with time. In figure 11-30A, the solid curve Y1 shows the velocity at any time, in this case a constant velocity. The distance traveled is equal to the velocity multiplied by the time; and with proper scale values, this distance is given by the numerical area under this (rectangular) curve; that is, area = height (or velocity) multiplied by length (or time). On the distance-time diagram, the sloping line X1 shows the total distance traveled at any instant of time; and the larger the step input the steeper the slope of the line in the distance-time diagram.

The distance traveled, x, must continue to increase as long as there is a positive value of velocity, y. When x is represented by a voltage,



12.305

Figure 11-30.—Integration of area operation.

there are limitations on its maximum value due to circuitry to be used.

The integral of a d-c voltage is a voltage with a constant slope as shown in figure 11-31. There is normally no need of integrating d-c voltages, but this effect is identical to the voltage wave for step inputs.

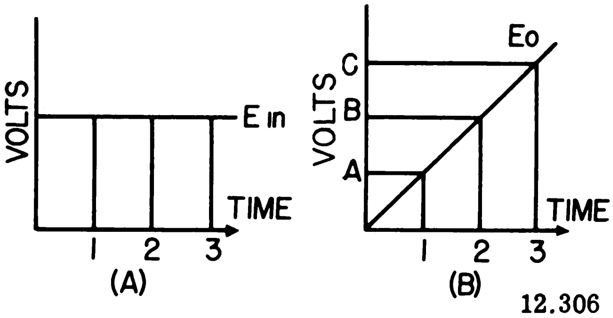


Figure 11-31.—Graphical representation of integration of a voltage.

An amplifier (fig. 11-32) is often used to improve the response and linearity of the integrating circuit. The capacitor, along with the input resistor and the load resistor, performs the integration. The circuit's output is based on the rate of change of the feedback capacitor (Cf). Its charging voltage is proportional to the potential difference across the amplifier, which is a function of its input signal. The amplifier maintains the charge or discharge of the capacitor in the linear portion of the RC curve.

ELECTRICAL DIFFERENTIATION

In differentiation we know the value of a quantity and we wish to find its rate of change. Assume that the computer is tracking a target and has solved its bearing rate. The computer must detect any change in this rate. It must know if the rate is accelerating and by how much and in what direction. The computer can solve this problem with a differentiating circuit.

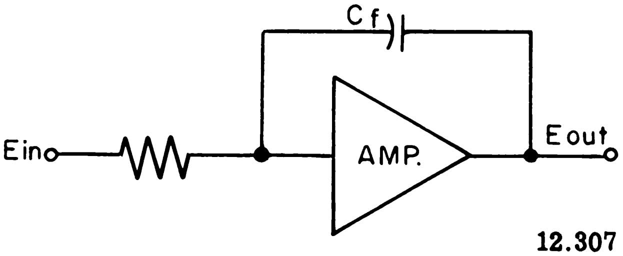


Figure 11-32.—Integrator circuit around an amplifier.

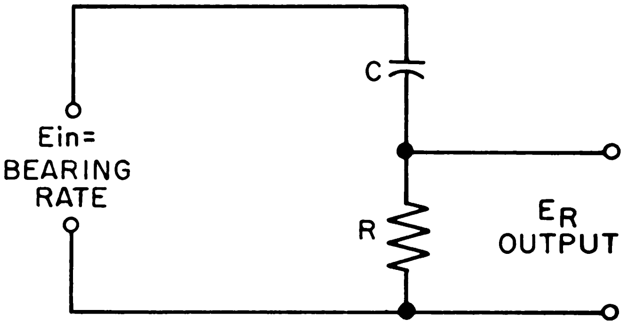


Figure 11-33.—Differentiating circuit.

The bearing rate is the known quantity, angular velocity, and its acceleration is the rate of change of the velocity, a derivative. Differentiating circuits are often referred to as derivative circuits.

As you know, in differentiating circuits (fig. 11-33), the output is taken across the resistor. The input to the circuit is a voltage proportional to the bearing rate. If the rate is constant the capacitor will charge to the input voltage, and when it is charged there will be no more current flow in the circuit. Obviously a voltage drop will appear across the resistor only when a current flows through it. Therefore, if there is no change in the rate and the voltage representing it, the output from the circuit will be zero volts, representing zero acceleration. If the rate changes, the capacitor will start to charge or discharge to the new level of the input voltage. Instantly a current, which is a function of the charging rate of the capacitor, will flow through the resistor. The circuit's output, which is the IR drop across the resistor, is therefore proportional to the rate of change of the bearing rate, or the acceleration of the rate.

SIMPLIFIED COMPUTING LOOPS

In this discussion we will connect some of the basic computing elements into a computing loop. This will help you to see the interrelations between the elements in a practical computer. At the same time it will tie the fire control problem to the computer. Quantities in the problem are expressed in the fire control symbols based on OP 1700, Standard Fire Control Symbols.

We will take a small segment of the problem and show a typical computer instrumentation. In the diagrams we will use symbolic figures to show a mathematical operation, and list some of the basic elements which may be used to perform the operation. The intent here is not for you to learn the entire problem or the entire computer. That will come later.

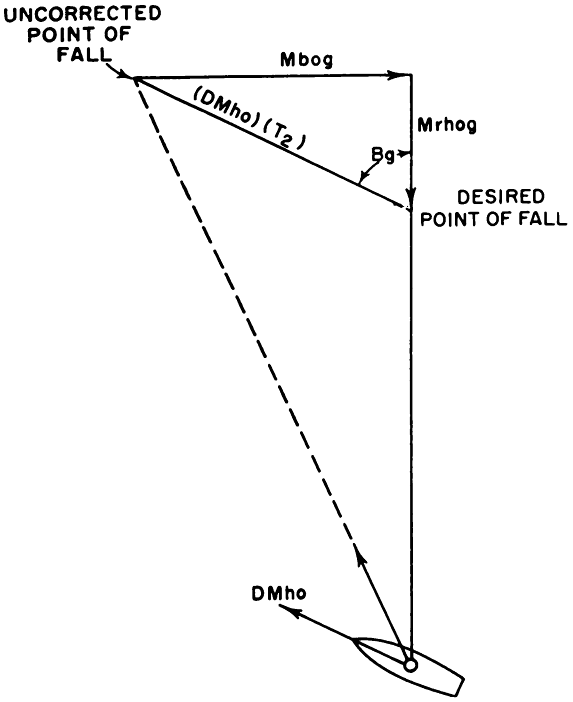
LINEAR RATE PROBLEM

The problem we wish to solve is diagramed in figure 11-34. We are firing a gun battery at a stationary surface target. The forward motion of the ship and gun is imparted to the projectile and will change both range and deflection, so that unless a correction is made, the projectile will miss the target.

We will assume that only the forward motion of the ship and the horizontal component of initial velocity are acting on the projectile. Ship's motion, forward velocity, is indicated by the vector DMho. The motion of the projectile due to the DMho during the time of flight T2 is equal to the product of [DMho] [T2]. The resultant motion of the projectile is resolved into two components:

Mrhog = Line of fire component of own-ship motion in range.

Mbog = Line of fire component of own-ship motion in bearing.



12.309

Figure 11-34.—Derivation of corrections for gun motion.

We will compute these corrections, which are equal to

$$\mathrm{Mrhog} = -\,[\mathrm{DMho}]\,[\mathrm{T2}]\,[\cos \mathrm{Bg}]$$
$$\mathrm{Mbog} = [\mathrm{DMho}]\,[\mathrm{T2}]\,[\sin \mathrm{Bg}]$$

The minus sign indicates that the range correction will be negative.

Figure 11-35 illustrates a network that may be used to compute the range and deflection correction for ship motion. We will assume that the inputs to the network are known and therefore only require the identification of the symbols for the new quantities.

R4 = range to aiming point
Ls = sight deflection
B = relative target bearing
Bg = relative gun bearing

Obviously the elements that a computer uses determine whether it is a mechanical, electromechanical, or electrical computer. We will show the mathematical operations and some of the computing elements that are used to solve this type of problem. Note that each element accepts and operates on the information furnished it. The elements solve their problems simultaneously and continuously.

The time of flight, T2, is a nonlinear function of range to the aiming point, R4. A cam or a nonlinear potentiometer may be used to obtain T2.

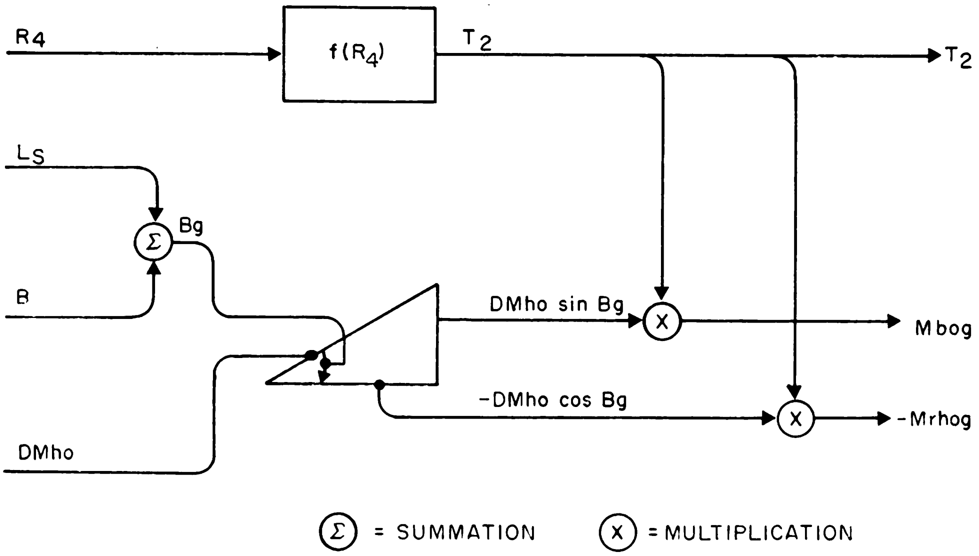
The summation of sight deflection, Ls, and relative target bearing, B, may be performed by a mechanical multiplier, a linkage mechanism, or an electrical summing network (summation network box).

The right triangle solver may be a component solver, an angle resolver, or an inductive resolver.

The multiplication problems may be solved by a mechanical multiplier, a linkage mechanism, a potentiometer circuit, or an amplifier.

DIGITAL COMPUTERS

Digital computers have only a limited application in present day surface ship weapon control systems. But they are used extensively in the Naval Tactical Data System (NTDS) and in the Polaris weapon system. Since digital computers are limited in application, the "Quals" do not require that you be examined on this subject. But additional use of digital techniques may be expected in fire control systems and in weapon direction systems. Therefore, to stay abreast of developments in the computer field, it is necessary to include digital computers and data



12.310

Figure 11-35.—Gun motion correction network.

conversion devices in your studies. The basic concepts of digital computers are covered in Basic Electronics, NavPers 10087-A. The coverage includes the fundamental circuitry, logic, and mathematics to provide you with a general understanding of digital computers. A more advanced coverage of the logic and mathematics of computers is contained in the Navy training course Mathematics, Vol. 3, NavPers 10073.

A computer can solve a problem only when the problem is stated in language that the computer can understand. As you know, the form of the information used in a digital computer is different from that used in an analog computer. The information may be the same, but the "language" is different. Therefore, the process of transferring data between an analog and a digital computer must include translation of the language. Specific codes which have no meaning outside of a computer are often used within the computer. The 307 we used in the example of force in a missile at the beginning of this chapter has a definite meaning in that particular circuit. It would have a different meaning elsewhere. The numerals in figure 11-2 would have no meaning to a digital computer, and the computer would not accept the information, for it is not part of its language. Consequently, a computer requires its input information to be coded into its language, and its outputs to be decoded into a form useful to the associated instruments.

The problem of data conversion is acutely evident in and around the Weapons Direction System (WDS) where it is interconnected to the NTDS. The later system is maintained by the Data Systems Technician, and uses digital computers. Data inputs to the WDS from the NTDS are in coded digital form. The WDS however, requires its input data in analog form. On the other hand, data flowing in the opposite direction, from the WDS to the NTDS, must be converted from analog to digital form. The principles and some of the basic devices used in the conversion are covered in the Navy training course Data Systems Technician 3 & 2, NavPers 10201. When the use of digital computers becomes more extensive in fire control systems, so as to justify their inclusion in the "Quals," this information will be included in this training course. This may be in the not too distant future, and you should be prepared. Study the basics of digital computers, and especially data conversion systems.

CHAPTER 12

INTRODUCTION TO FIRE CONTROL RADAR

The tactical use of a radar determines the requirements which it must meet, and these in turn determine its circuits and components, and its operating characteristics. Fire control radar is one of the broad classes of shipboard Navy radars. The other classes are search radar and special radar. Basically, radar is a data-sensing element. Since the purpose of a fire control system is to destroy a selected target, the radar's job is to obtain as much accurate data about the target as possible. The more data the system has, the more likely it is to score a hit on the target.

Because fire control radar has so many uses and requirements, we have divided its coverage into three chapters. In this chapter we will discuss, in general terms, the classes of fire control radars, their applications, features, and operational characteristics. The next chapter will deal with pulse-modulated fire control radars, and the following chapter will be about pulse-Doppler and continuous-wave (c-w) fire control radars.

The fundamental principles of radar are covered in Basic Electronics, NavPers 10087-A. We will review the principles of operation and the essential sections of a basic radar in this chapter to be sure you have the necessary background. Note that we did not say the review would give you this background.

BASIC PRINCIPLES OF RADAR

Radar, in brief, works on the echo principle. The radar radiates waves of radio-frequency (r-f). The waves, for all practical purposes, can be considered to travel in a straight line until all their energy is expended. If the waves strike an object, some of the r-f energy is reflected, and is called an echo. The echo returns to the radar by a reciprocal path and indicates the presence of an object in the wave's path. To be really useful the radar must be able to determine the exact location of the object.

RADAR RANGING

Radar ranging is based on the facts that the r-f energy travels at a constant velocity in a straight line and that an object in the wave's path will reflect some of the energy that strikes it. The wave's velocity is independent of its energy level. Thus a weak echo will travel at the same speed as the strong transmitted wave. Radar determines range by measuring the time it takes the energy to travel from the radar antenna to the target and back again to the radar. Since the velocity of the energy is constant, the distance through which the reflected energy has traveled varies linearly with time. Because the waves must travel to the target and back again before the echo can be detected, target range is half the total distance traveled.

The velocity of the r-f energy, and its time of travel to the target and back again, can be used to calculate target range. The velocity of r-f waves in space is the same as that of light, 161,000 nautical miles (186,000 land miles) per second. Obviously, 161,000 miles is too large a figure for our use. Therefore, the unit used to measure time is the microsecond (a millionth of a second). The r-f energy travels approximately 328 yards per microsecond, or one nautical mile in about 6.2 microseconds. Neither own ship nor target motion will change the r-f energy's velocity, but they may affect the frequency of the r-f energy. We will consider this later. The r-f energy is reflected by the target instantaneously and no time is lost at the target. There is some delay in the radar's receiver, the transit time of the receiver, but this is a constant, characteristic time delay and is compensated for.

The formula for radar range is:

$$\begin{array}{c}\text{Radar range} \\ \text{(in nautical miles)}\end{array} = \frac{\begin{array}{c}\text{Microseconds between} \\ \text{transmission} \\ \text{and echo return}\end{array}}{12.4}$$

The figure 12.4 is the time it takes the r-f energy to travel two nautical miles; remember, the reflected energy must make a round trip between own ship and target. It would be impossible for a person to count off the microseconds, but it can be done with ease electronically, and an oscilloscope can be used to graphically display the passage of microseconds. Since range is a linear function of time, the scale associated with the oscilloscope's sweep, which represents time, can be graduated in units of range, (miles or yards). Oscilloscopes are covered in Basic Electronics, NavPers 10087-A.

To use the range formula, the radar must be able to pinpoint exactly when the energy reflected by a target left the radar. One method of determining the exact time the reflected energy left the radar is to pulse-modulate the radar transmitter. A short signal pulse triggers the radar transmitter and causes it to start radiating r-f energy. The radar transmits for a short time, then shuts down. The instant the transmitter starts to radiate is zero reference time. The trigger pulse also starts the radar receiver's timing system. While the transmitter is shut down the radar's receiver "looks" for a return echo from that burst of r-f energy. After a time which depends on the pulse repetition rate of the radar, the process is repeated.

There are other methods of determining the exact time the transmitted energy left the radar. Later when we discuss c-w radars we will cover another method.

TARGET LOCATION

A surface target can be located by its range and bearing. To define the location of an air target, range, bearing, and elevation or target height are needed. Fire control radars compare the strength of the echoes returned by a target to determine bearing and elevation. To understand the principles involved we must first discuss the form of the transmitted energy in space.

The radar antenna forms the r-f energy into a narrow beam. The center axis of the beam corresponds to the boresight axis or line of the antenna (fig. 12-1). The beam is divided into quadrants by a vertical axis and a horizontal axis. The beam's axes are mutually perpendicular and intersect at the boresight axis of the antenna.

The amount of r-f energy or power density is greatest along the beam's centerline. The beam's power density decreases by an amount proportional to the displacement from the beam's centerline axis. Therefore, if a target is not in the center of the beam, it will return a weaker echo than if it is exactly on the beam's centerline axis. Generally, the radar beam is swept over the area surrounding the target in such a way that the returning echoes vary in amplitude with the position of the target with respect to the beam's centerline axis.

A target at a given range located on the vertical axis but in the upper fringe of the beam would return a weak echo. As the beam is elevated, the strength of the echo increases as the boresight axis approaches the target's position. When the beam's boresight axis intersects the target, the maximum echo will be returned. If the beam continues to elevate, the echo's strength will be reduced in proportion to the distance of the target below the boresight axis. The same principle is applied to determine target bearing, except that the amplitude of the echo varies in respect to the horizontal beam axis.

The radar must provide the fire control system with continuous bearing and elevation information. Obviously, if we keep moving the radar antenna to locate the target in the beam, the information furnished the system would be very rough indeed. Instead, the beam is scanned systematically about the antenna's boresight

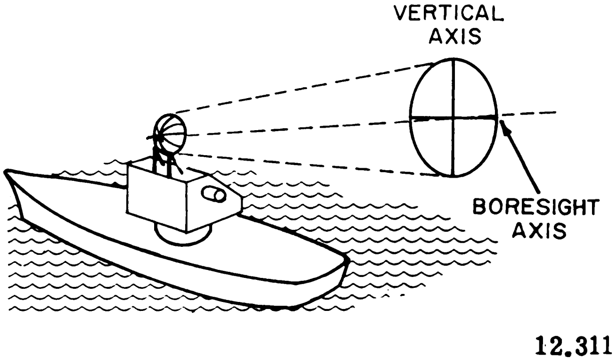


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Figure 12-1.—Beam pattern.

axis. The principle of echo strength versus target position in the beam is still used. We will cover beam scanning later in the chapter.

ELEMENTS OF A RADAR SET

Fire control radar sets vary greatly in detail and in function. They may be very simple or, if more accurate data is required, they may be highly complex and sophisticated. However, the same basic functional sections are found in all radar sets. Thus, any radar set can be visualized as consisting of 5 basic sections—synchronizer, transmitter, antenna system, receiver, and indicator.

These sections, shown in figure 12-2, are familiar to you from your study of basic radar. Therefore, we will not dwell on them. Only a very brief functional description is included here.

RADAR SECTIONS

Synchronizer

The synchronizer is the timing unit. It is the heart of the entire system. It produces trigger pulses which control and coordinate the circuits of the system so that each operates at the correct time. In pulse-modulated systems it governs the number of pulses the transmitter produces in each second (called the pulse repetition frequency (PRF) or pulse repetition rate (PRR). It coordinates the sweep voltage in the indicator tube with the firing of the transmitter, and contains provisions for delaying the beginning of the sweep to give special types of display, such as B, E, A, PPI. The synchronizer contains the circuits which generate the range marker voltages and the trigger pulses which activate the indicator tube when the trace starts to appear on the screen. Pulses supplied by the synchronizer are also used to control associated equipment used with the system. The synchronizer may be known by other terms or names such as keyer or timer.

A missile fire control system may use two separate radar sets to perform the tracking and guidance functions. When sets are grouped in this manner, a separate synchronizer unit (called a master synchronizer) is used to generate timing pulses for each radar set and to coordinate their operation.

Transmitter

The transmitter's purpose is to generate and deliver pulses or continuous waves of r-f energy to the antenna system where it is radiated into space. In fire control radars, the generated r-f energy is usually in the S, C, or X bands. The S band has a frequency range from approximately 1550 to 5200 mc, while the C band's range is from 3900 to 6200 mc, and the X band's range is from 5200 to 10,900 mc. The symbol mc stands for megacycle or one million cycles per second.

Basically, the transmitter is an r-f oscillator that uses magnetrons, klystrons, or traveling wave tubes to generate microwave energy. The

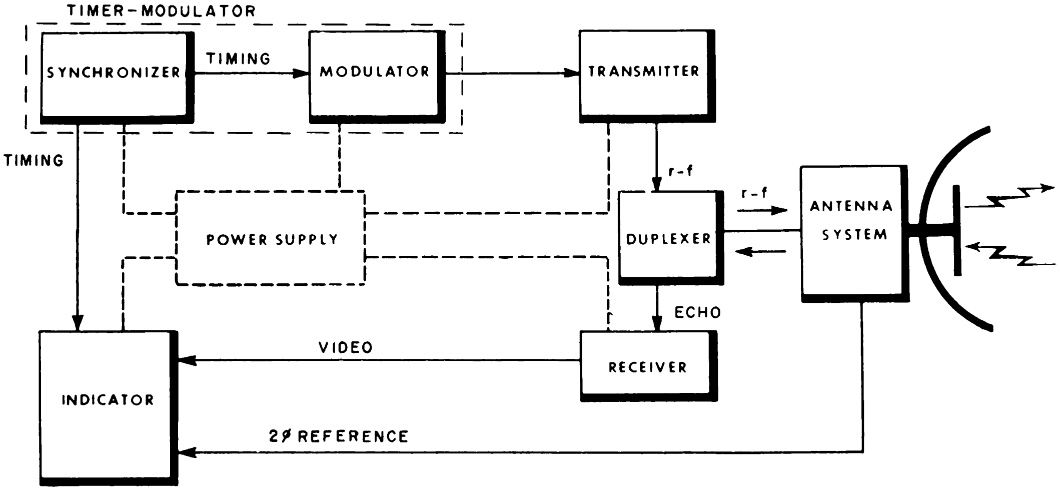

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Figure 12-2.—Block diagram of basic radar set.

operation of the transmitter is controlled by a signal received from the synchronizer. Strictly speaking, control of the transmitter, such as turning it on and off, is provided by a section within the transmitter called the modulator. In pulse-modulated radars, the modulator is a special circuit designed to supply power to the r-f oscillator when it receives the appropriate signal from the synchronizer. C-w radar transmitters are also controlled by a modulator. The modulator may have another name, but its function is the same as that of any modulator—to superimpose intelligence on the carrier. Many missiles home on energy reflected from a c-w radar whose carrier is frequency-modulated for identification. Coding the illuminating signal prevents the missile from homing on a target illuminated by a radar other than the missile's companion illuminator.

Antenna System

The antenna system has two general purposes. It radiates microwave energy developed by the transmitter, confining the waves into a narrow beam. In addition, it receives the echo signals from targets and applies them to the receiver. The antenna system consists of waveguides, switching tubes, a reflector for beaming the radiated energy, a mechanism for nutating the feed during operation, and servo units which position the antenna reflector.

Since the same antenna is generally used for both transmitting and receiving, it is necessary to switch it alternately from one component to another. This action is accomplished by the DUPLEXER which consists principally of the TR (transmit-receive) tube and the ATR (anti-TR) tube. These tubes contain gas at a low pressure. Arc-discharges take place in the tubes when the transmitter pulse is applied to the waveguide containing them. The TR tube prevents the transmitted pulse from entering the receiver and damaging the sensitive crystal mixer. When the transmitter is idle, both tubes are de-ionized, and the ATR tube serves to prevent reflected echoes from entering the transmitter, allowing them to flow into the receiver.

Receiver

The receiver is an extremely sensitive superheterodyne containing circuits with bandwidths capable of passing pulses of the type emitted by the transmitter. It is important that the receiver generate as little local noise voltage as possible to avoid masking weak echo pulses.

The signals from the antenna are usually applied first to a crystal mixer where they are mixed with the output of the local oscillator, a reflex klystron tube. The i-f output resulting from the mixing process is then amplified in a number of i-f stages. In most radar receivers the intermediate-frequency value is either 30 or 60 megacycles. A video detector converts the i-f energy into video pulses. After passing through one or more stages of video amplification, the signals are applied to the cathode-ray indicators and range and angle track circuits.

Radar receivers employ automatic frequency control to keep the receiver intermediate frequency from drifting. A typical method is as follows: A sample of the transmitted frequency is coupled to a separate mixer, called the AFC mixer, to which some of the output from the klystron local oscillator is also applied. The AFC mixer develops the difference frequency of the two and applies this signal to a discriminator circuit. The discriminator output voltage is zero when the correct intermediate frequency is produced. But if the receiver local oscillator attempts to drift off frequency, the discriminator produces a d-c voltage which is positive or negative depending on whether the local oscillator frequency is too high or too low. The d-c output of the discriminator is then applied to the klystron local oscillator. This corrects the klystron frequency until it differs from the frequency of the outgoing pulse by the proper amount.

Indicator

The indicator or presentation system accepts the radar data such as video pulses, the range-marker voltages, and sawtooth timing waves, and presents a visual display on cathode-ray tubes. An indicator assembly contains the cathode-ray tube and various electronic circuits necessary for presenting the desired information on the CRT. These circuits include video amplifiers, diode clamping tubes, and the controls for adjusting the visual pattern.

Two general types of presentation are used in radar indicators—deflection-modulated and intensity-modulated displays. In the deflection method, the video pulse causes a momentary deflection of the cathode-ray electron beam and produces a pip in the trace to indicate a target echo. In the intensity method, the video signal is applied to the element of the CRT which controls the intensity of the electron beam, and the resulting target image is a bright spot of light. The A-scope is an example of the deflection method, and the PPI is a typical intensity presentation.

Sawtooth timing waves of voltage or current are applied to the deflection circuits of the CRT to produce the time trace or sweep in the pattern. The synchronizing pulse which triggers the modulator and transmitter also serves to coordinate the start of the sweep with the action of the transmitter to make range measurements possible. Target bearing in PPI displays is indicated by synchronizing the position of the sweep line on the CRT with the position of the antenna.

In addition to video pulses, rangemarker pips, and sweep voltages, a square wave pulse is applied to the indicator tube which blanks the beam between sweeps so that retrace lines do not appear on the screen.

CLASSES OF FIRE CONTROL RADARS

Fire control radars may be classified by their general use, by their method of modulation, by their frequency or wavelength, by their method of scanning, or more frequently, by their method of transmission. Of course, there are other methods of classification, but the ones listed are used most frequently.

When fire control radars are classified according to use or the weapon they direct, they can be divided into two general categories: (1) gun fire control radars, and (2) missile fire control radars. It would be possible, and correct, to include another category called gun and missile fire control radars, because some fire control radars determine the position of enemy targets and direct the ship's guns and missile launchers simultaneously. But for our purposes let's stick to the two categories listed above.

We can divide fire control radars by their method of transmission into three general classes: pulse-modulated, continuous-wave, and pulse-Doppler radars. Pulse-modulated radars transmit pulses of r-f energy. The radar's pulse repetition rate, PRR, determines the usable range of the radar. The time between the transmission of the r-f energy and the echo return is measured electronically and displayed graphically by a cathode-ray tube, CRT. Pulsed radar, with its precise measurement of transit time, can measure range accurately.

Continuous-wave (c-w) radar, as its name implies, radiates r-f energy continuously. The frequency of the r-f energy in the echo is changed by a moving target. This change in frequency is called Doppler shift. The Doppler shift is used for target detection, and to indicate the target's range rate. It is possible, by the use of filter circuits, to reject all targets except those traveling at or near a selected velocity. Since the radar transmits continuously, it can provide target information without interruption. It is therefore an ideal radar to illuminate a target for a semiactive homing missile. The radar has a transmitting antenna and system aboard ship and a receiving antenna and system in the missile. But, because the radar transmits continuously, it has no pulse reference by which it can measure transit time and range directly.

Pulse-Doppler radars combine the best features of c-w and pulsed radars. The name tells us the radar is pulse-modulated and that the Doppler shift in the returned r-f energy is used. The PRR is much higher than that of a conventional pulse radar and the pulse length is longer. A pulse-Doppler radar, therefore, transmits a greater percentage of the time than a conventional pulse radar. A radar that transmits more than ten percent of the time has some of the characteristics of continuous transmission, and is considered to be a c-w radar. But since it is pulsed, a pulse-Doppler radar can measure range by using transit time. The Doppler shift can be used to obtain a measure of target's range rate and as a means to operate the radar receiver with a narrow bandwidth, and thereby reject unwanted targets and noise.

You probably have seen fire control radars classified by the frequency of their r-f energy. As a matter of fact, we classified them in this manner when we were discussing the transmitter of a basic radar. Later in the chapter we will discuss the advantages of having the transmitted frequency in the microwave region. In this region, radar components are often designated by their wavelength design.

FUNCTION OF RADAR IN FIRE CONTROL SYSTEMS

A radar set is designed for the particular fire control system in which it is to be used.

The radar's capability must be compatible with its functions in that system. Fire control radars have many uses and are very versatile. They are used to detect and track surface and air targets, guide a missile to a target, illuminate a target for a missile's homing system, operate with a radar beacon, transmit and receive coded identification and command signals, and to spot (correct) the fall of shot for surface fire.

Target Position Determination

The first job performed by the radar is to determine target position with respect to own ship. The radar is normally assisted in acquiring the target by signals from the designation system. However, to decrease target acquisition time the fire control radar beam is scanned over the area surrounding the designated target position. Once the target is acquired the radar's scan pattern is reduced to concentrate on the target.

The fire control solution is based on the radar's measurement of the line of sight to the target. In the design of fire control radars, emphasis is placed on extreme accuracy in range and position measurements. To meet this need, high carrier frequencies are used and pulse systems operate at high PRR. The radar antenna usually has parabolic reflectors or microwave lens systems that form the radiation into narrow "pencil" beams.

Target Tracking Systems

Once the target is centered in the beam, the radar tracks the target to provide continuous line of sight information. Tracking is usually accomplished automatically. The tracking systems operate on the same principle as the servosystems that you have already studied. In a servosystem, the error signal is the input to a servoamplifier. The output of the amplifier is the input to a servomotor which drives the system until the error has been eliminated.

If the radar is not "on target" in range, there will be an error signal from the range error detecting circuits. This error signal is used to provide a signal voltage to the range servo that drives the ranging circuits to take out the error signal. Likewise, if the radar antenna is not trained directly at the target, there will be an error signal output from the train error detecting circuits. This error signal is used to develop a voltage input for the train servoloop to drive the antenna mount until the error has been eliminated. The elevation tracking system will keep the antenna on in elevation. When the target is moving, tracking is a continuous process.

Spotting

Radar provides a means of spotting surface fire which is independent of conditions of visibility. Shell splashes appear on a radar scope as fluctuating echoes which last for several seconds. The radar operator can count off or estimate the distance in range and bearing between the target and the splashes, and correct the next salvo to hit.

Radar Beacon Operation

Radar beacons are used to supplement the natural targets of the radar. Moreover, each installation has its own code and therefore is an improvement over the natural target. Beacons will operate only when a signal with the proper frequency and code is received. The radar transmitter and beacon receiver are tuned to the same frequency. The beacon starts to transmit when it receives an r-f signal from the radar. The beacon transmits back to the radar receiver. Thus the beacon transmitter and radar receiver must be tuned to the same frequency. This frequency, however, does not have to be the same as the radar transmitter's and beacon receiver's. The frequencies selected would depend on the application. Beacons are used in shore bombardment as a fixed target ashore which acts as a reference point. Some guided missiles contain beacons for the transmission of data between the missile and the fire control radar aboard ship. Some phases of missile and radar alignment and testing require the use of beacons.

Missile Guidance

Fire control radar is the source of guidance for both the beam-riding and the semiactive homing missiles. The missile is like a puppet on the radar's electromagnetic string, dancing to the commands of the radar. Naturally, each type of guidance makes different requirements on the radar. But basically the radar in both systems operates like an automatic tracking radar, with the major exception that the error-detecting circuits and the servocontrol system are in the missile. The position of the guidance radar antenna is controlled by the fire control system aboard ship. The guidance radar either follows a target-tracking radar directly or is programmed so that its radar beam closes with the target is some prescribed manner.

A beam-rider missile receives guidance data directly from the ship's radar beam, and the target is not part of the guidance link. The radar's guidance beam is narrow to obtain tight control of the missile. A wide-angle, low-powered capture beam is radiated by the radar to initially capture the missile in the guidance beam. With semiactive homing missiles the target acts involuntarily as a reflector for the illuminating radar's beam.

REQUIREMENTS OF FIRE CONTROL RADAR

Now that we have a general idea of the functions that radar performs in fire control systems we can look at the requirements and characteristics of its transmission and receiving systems. We will keep the discussion general, leaving the details to a later chapter and course.

TRANSMISSION

The frequency of the radiated r-f energy is called the radar's carrier frequency. The carrier frequency of fire control radar is superhigh, being in the S, C, or X bands. The use of the higher frequency makes it possible to use smaller antennas than when the lower frequencies are used and still obtain very narrow beams. Furthermore, the higher frequencies produce better target echoes and make possible the detection of smaller targets.

Superhigh frequencies have some disadvantages. Special microwave components are necessary to generate these frequencies, and waveguides are needed to conduct them. Conventional amplifiers have serious limitations at these frequencies. Therefore, it is necessary to heterodyne the r-f return with a signal from a local oscillator and depend on increased i-f amplification to obtain a usable output.

Transmitter Power

The useful power of the transmitter is the radiated energy. It takes a certain amount of echo signal power to affect the radar receiver strongly enough to produce a usable output. The more powerful the transmitter, the stronger will be the echo from a target at a given range. Hence the effect of a more powerful transmitter is to increase the radar's range. Long-range search radars, therefore, require a very powerful transmitter, while fire control radars with a limited effective range require a less powerful transmitter.

The power output of a radar represents a compromise between maximum range and component size. As a general rule, the higher the power rating of a component the larger its size and the more heat that is generated during normal operation.

Since a pulsed radar is not transmitting during most of its total cycle, the average power is quite low when compared with the peak power during the pulse time. Pulse width, pulse repetition rate, average and peak power, and the duty cycle of a pulsed radar are explained in Basic Electronics, NavPers 10087-A. Be sure all these quantities are familiar, as they are important to your understanding of pulsed radar operation. In a c-w radar that transmits continuously, the average power is equal to the peak power.

Directivity

Fire control radar must be able to pick out a particular target and determine its exact range, bearing, and elevation. Thus it must radiate and receive most of its energy in a particular direction. A radar's ability to concentrate on a point in space or a target is determined by the shape of its beam. The beam shape or pattern depends on several factors, among which are: (1) the directivity of the antenna, (2) the effect of frequency on propagation, and (3) the method and length of radiation.

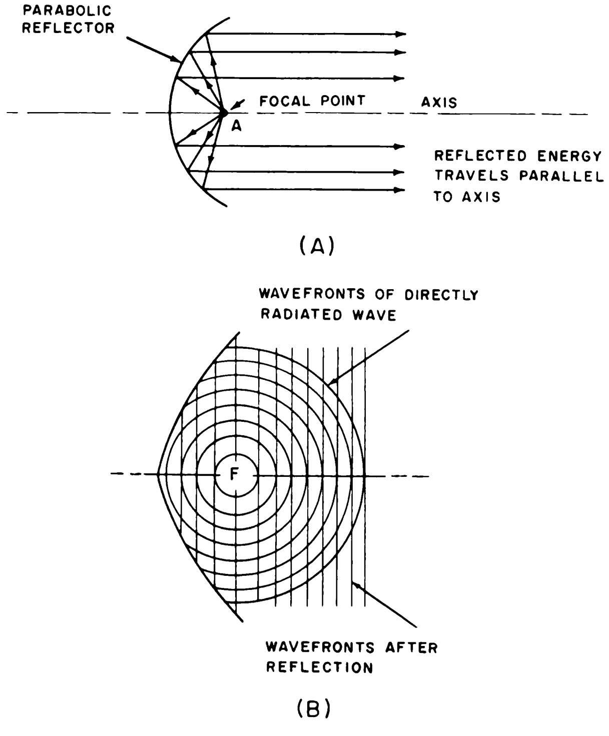
Radar Antenna

The directivity of an antenna refers to the sharpness or narrowness of its radiation pattern. The beam pattern produced by an antenna depends primarily on the shape of the reflector.

The type of reflector generally employed in fire control radars is the parabolic disk. It is similar in appearance to the reflector used in automobile headlights. One of the important advantages of radar operation in the microwave region of the electromagnetic spectrum is that microwaves have properties and characteristics similar to those of light. This permits the use of well known optical design techniques.

The action of the reflecting surface of the reflector is a result of its parabolic shape and the fact that the rays striking and reflecting from the metallic surface make equal angles with the surface at the point of reflection. This action is illustrated in figure 12-3. In A of the figure, consider that the focal point is a feedhorn radiator and is a point source of energy. Electromagnetic energy is emitted from a point source in spherical waves like ripples that fan out from a pebble thrown into a pond of still water. The primary purpose of the parabolic reflector is to change the spherical wavefronts of the radiated energy into flat (plane) waves and focus them into a circular beam. Part B of figure 12-3 shows spherical wavefronts coming from a radiating feedhorn at the focal point of a parabolic reflector. As the waves strike the reflector they are straightened and concentrated into a narrow circular beam of energy containing parallel flat wavefronts.

When the radar is receiving reflected energy, the incoming rays are concentrated and focused on the feedhorn when they enter the dish as parallel rays. The waves reflected from a distant target can be considered to be parallel if they were transmitted in this form. The action of the reflector during reception can be visualized by reversing the arrowheads in part A of the figure. Therefore, we can state that in any antenna system the transmitting and receiving patterns are essentially the same. For this reason one antenna can be used for transmission and reception. The parabolic reflector produces a "pencil beam" in which most of the energy is confined to a small cone of nearly circular cross section. The concentration of the energy into a beam increases the amount of radiation illuminating a target.


PARABOLIC REFLECTOR
FOCAL POINT
AXIS
A
REFLECTED ENERGY TRAVELS PARALLEL TO AXIS
(A)
WAVEFRONTS OF DIRECTLY RADIATED WAVE
F
WAVEFRONTS AFTER REFLECTION
(B)

1.49.25.226
Figure 12-3.—Principle of parabolic reflector.

Scanning

In addition to radiating and focusing energy into a narrow circular beam, the antenna system must provide a means for searching for a target and for determining its position. This process is called scanning or lobing. Lobing can be divided into two broad categories—(1) sequential lobing and (2) simultaneous lobing. Examples of sequential lobing are conical scanning and lobe switching. Simultaneous lobing is best illustrated by a fairly recent lobing technique called monopulse. We shall discuss scanning methods in considerable detail later.

RADAR RECEIVER

A radar receiver detects the echo signal coupled to it through the r-f lines and amplifies the signal many times. The echo is extremely weak and the receiver must have a very high gain to produce a usable output. As you know, the signal cannot be amplified readily at the carrier frequency; therefore radar receivers are of the superheterodyne type. But let us start this discussion with the r-f energy from which the receiver must extract the echo signal.

Although we tend to think that a radar pulse contains a single frequency, it actually is composed of a wide band of frequencies centered about the carrier or fundamental frequency. The characteristics of the echo are determined primarily by the radiated energy. The echo, therefore, contains approximately the same frequency distribution as the radiated pulse. (Target motion may vary the frequencies in the echo somewhat. We will take that up in the chapter on pulse-Doppler radars.) Thus to reconstruct the echo at the intermediate frequency the receiver's bandpass must be large enough to pass all the frequency variations in the r-f pulse. If the receiver will not pass all the frequency variations the reconstructed echo will be distorted and some of its strength will be lost. The receiver can ill afford either distortion or loss in the echo signal.

The receiver's amplifiers are tuned to the intermediate frequency but have a wide bandwidth to reduce distortion of the echo shape and to obtain maximum amplification of the signal. The bandwidths of radar receivers range from one megacycle to five megacycles. The gain of the receiver should be as uniform as possible over the entire bandwidth. But the gain of an amplifier decreases with any variation of the signal frequency from its tuned frequency. This much variation in gain must be accepted but can be compensated for by increasing the number of stages.

A receiver bandwidth that is too wide however, permits too much noise to be amplified. The noise we are referring to here is the various random disturbances present in all electrical circuits which generate small voltage variations. Since the amplifier is tuned to pass and amplify voltages within a frequency band, it will reject noise not in the bandwidth but must accept noise voltages with a frequency in the bandwidth. Thus the accepted noise voltages are amplified along with the signal voltage. If the signal is not at least as large in amplitude as the noise voltage at the receiver's input stages, it cannot be recognized at the receiver's output, and therefore is useless.

A high signal-to-noise ratio is required so that the receiver can detect a weak signal from a distant target and override the noise generated in the receiver. The amount of noise that will pass through the receiver is affected by the bandwidth of the receiver. In general, a reduction in bandwidth reduces the noise voltage in the output but does so at the expense of distortion in the pulse shape.

We have two contradictory requirements; the bandwidth must be large to pass the frequency variations in the echo pulse to reduce distortion, and at the same time it must be as small as possible to increase the signal-to-noise ratio. Hence the bandwidth of the receiver represents a compromise; some distortion and loss of signal strength are accepted to obtain a high signal-to-noise ratio. The amount of distortion which can be tolerated is the limiting factor in increasing the ratio by a reduction in bandwidth.

The intermediate frequency is the resultant frequency obtained by mixing the carrier frequency and the receiver's local oscillator frequency. Any frequency drift of the carrier or local oscillator frequency will cause the intermediate frequency to change by the same amount. The receiver is tuned to the intermediate frequency and a change in frequency will reduce the gain of the receiver.

Since the carrier and local oscillator frequencies often drift from the proper value, some means of frequency control is necessary. An automatic frequency control (AFC) is used in most radars to compensate for frequency variations. The AFC circuit causes the local oscillator to follow variations in the carrier frequency so that the intermediate frequency is kept constant. Most AFC circuits consist of a frequency discriminator connected to one of the i-f stages. The discriminator converts frequency variations from the standard into voltage variations.

The voltage variations are used to control the frequency of the receiver local oscillator. When the correct intermediate frequency is reached, the discriminator output becomes zero. AFC circuits will be discussed more completely later in this course.

Gain Control

If you have ever examined your household radio set, you know that it has an automatic volume control (AVC) circuit to keep the output constant over varying levels of carrier power. The radar receiver has one or more circuits that accomplish the same purpose as the radio AVC circuit by varying the gain of the radar receiver with the power level of the input signal.

If a gain-control circuit were perfect, a target would produce an A-scope indication that was the same size regardless of the range of the target. The indication would depend only on the size of the target. But a perfect gain-control circuit like that just described is impossible because the strength of an echo varies inversely as the fourth power of the range. In other words, a target at a 10-mile range produces a signal 10^4 times more powerful than the same target of a 100-mile range. No radar receiver could increase the gain that much in addition to the large gain required to reproduce the signal on the scope. The normal gain of a receiver is so great that it is subject to blocking by large signals. A great increase in gain also lowers the signal-to-noise ratio considerably. Therefore, a form of "inverse" gain control is necessary—that is, instead of increasing the gain for small signals, the gain is reduced for large signals. In this way, the danger of blocking is reduced, and the fundamental purpose of gain control—that of size of the output—is accomplished to controlling the greatest extent possible.

There are two main types of gain control used in radar sets. The first of these, automatic gain control (AGC), varies the gain of the receiver as a function of signal strength. Whenever a strong signal is received the gain is reduced by an amount proportional to the size of the signal. This prevents blocking of the final stages of the receiver. A weaker signal, however, would have less effect on the AGC circuits and the gain would not be reduced quite so much. AGC circuits are also known as instantaneous automatic gain-control (IAGC) circuits.

Another type of gain-control circuit is the sensitivity time-control (STC) circuit. The STC circuit reduces the gain of the receiver immediately after each transmitter pulse and increases the gain with increasing range in an attempt to cause a given target to produce an echo of constant size, regardless of range. STC reduces sea return because the gain is low at short range.

Receiver Sensitivity

The SENSITIVITY of a radar receiver is its ability to respond to weak echoes. The sensitivity of a radar receiver does not depend on the maximum amount of gain obtainable but on the noise level of the receiver. In other words, the gain could be increased many times above a given figure, but receiver noise would be amplified so greatly that a weak signal could not be seen among the "grass" and "clutter" produced on the indicator scope by the noise. Thus, the noise level of a receiver places a limit on the sensitivity of the receiver. The noise level depends on several factors. The signal-to-noise ratio in the first receiver stage is most important. Increasing the gain increases the noise level as well as the signal level. Receiver gain, therefore, is the result of a compromise between signal amplification and noise amplification.

Increasing the bandwidth of the receiver increases the noise level because noise from a wider frequency range is subject to amplification by the receiver. Yet the bandwidth must be wide enough to accommodate the essential frequencies in the radar pulse. The bandwidth, therefore, is a compromise based on frequency response and noise.

Target Resolution

A fire control radar must be able to distinguish between two or more targets which are located close to one another. The ability of a radar to give separate range, bearing, and elevation indications of individual targets is called resolution. Two or more targets at the same bearing and elevation, but at different ranges, must be separated by a certain minimum distance before they can be seen as separate indications on a radar scope. The length of time the transmitter is turned on determines the range resolution of the radar. If, for example, a radar's transmitted pulse is six microseconds long, it would get overlapping echoes from targets less than a half mile apart. That is, before the trailing edge of the transmitted pulse is returned from the first target, the leading edge of the pulse would have encountered the second target, and when reflected would meet the trailing edge of the transmitted pulse at the first target, so the receiver receives an echo nearly twice as long (12 microseconds) as the transmitted pulse.

Hence most fire control radars transmit extremely short pulses—in the order of a few tenths of a microsecond.

Likewise, targets at the same range but with different bearings and elevations must be separated by a certain minimum displacement before they can be seen as separate indications on a scope. The minimum displacement is known as the bearing and elevation resolution. The radar beam pattern determines the bearing and elevation resolution. Fire control radars have highly directional antennas with a carrier frequency in the microwave range to obtain small beam patterns.

Gating Circuits

Some radar receivers have a gating circuit that controls receiver action. The gating circuits operate on a single set of signals or on a particular echo. The desired target is normally selected by range. The signal from a particular target is placed in the range gate. The radar's gating circuits detect the presence of a signal in the range gate and start to work. The gating circuits generally control the following actions: indicate that the radar is locked on; change the type of scan; start the fire control computer to tracking the target; feed the tracking information for this target into the radar's tracking network; and energize the AGC circuits which maintain a constant receiver gain for the desired target.

INDICATORS

The video signal from the output of the radar receiver is fed to the indicator unit. The indicator unit consists of an indicator scope and the electronic circuits that are necessary to present the desired information on the scope. In this discussion we shall consider only the methods of presenting the desired information on the radarscope, and the external operating controls for the radar indicator scope. The electronic circuits required to operate the scope are considered in detail in Basic Electronics, NavPers 10087-A.

Comparison with Oscilloscope

The type of scope used by most radars is similar to the type used in fast-sweep test oscilloscopes. The radarscope uses a rapid linear sweep with time intervals in microseconds.

All cathode-ray tubes have a few common elements. There is an electron gun, that produces a beam of electrons. The face of the tube is covered on the inside surface with a phosphor coating that emits light when excited by the electron beam. The walls of the tube are coated with a conducting material that is kept at a high potential with respect to the cathode. This conducting material acts as an anode and collects the electrons after they have excited the phosphor coating on the face of the scope. Most cathode-ray tubes have one or more grids, as well, to regulate the electron beam in direction and intensity.

Methods of Deflection

The basic difference between cathode-ray tubes lies in the method by which the electron beam is deflected, or moved, across the face of the tube. There are two widely used methods of deflecting the electron beam. One is known as ELECTROSTATIC deflection and the other as ELECTROMAGNETIC deflection.

ELECTROSTATIC DEFLECTION.—The simpler method is electrostatic deflection. Four plates—two horizontal and two vertical—are in the tube. Each plate is an equal distance from the center path of the electron beam. (See figure 12-4A.) In an electrostatic tube using type-A scan, the sweep is caused by applying a linear sawtooth voltage to the vertical deflection plates. As the electric field between these plates is increased linearly, the electron beam is deflected across the face of the tube in a horizontal sweep. Incoming signals are applied to the horizontal deflection plates, where they cause the beam to deflect up or down on the face of the tube. The electrostatic cathode-ray tube is focused by changing the potential on the first anode in the neck of the tube. Most tubes of this type are used in type-A scopes and provide a range-only indication. Some tubes of this type are used for B-scope presentation, although the sweeps are not generated quite like those just described for the A-scan. Electrostatic scopes are used extensively in oscilloscopes and small indicator scopes. However, the larger the face of the tube, the greater must be the deflecting voltage on the deflection plates; hence, electrostatic scopes that are more than 7 inches in diameter are rare.

ELECTROMAGNETIC DEFLECTION.—In an electromagnetic cathode-ray tube, two coils just outside the tube are substituted for the deflecting plates of the electrostatic tube. A magnetic field, and not an electric field, causes the sweep in this tube. Remember that the strength of a magnetic field varies directly with the current in the coil. Thus the current, rather than the voltage, must be a linear sawtooth wave in order to produce the sweep in an electromagnetic tube. (See figure 12-4B.)

The electron gun in a cathode-ray tube requires some system to focus the electron stream into a beam. This is done either electrostatically by means of electrodes inside the tube, or magnetically by means of an external electromagnet or permanent magnet.

METHODS OF DISPLAYING INFORMATION

There are many methods of visually presenting the information obtained by a radar. The method used depends on (1) the type of information to be presented, (2) the use to which the information is to be put, and (3) the type of radar.

Four of the most common types are discussed here. These are (1) the A-scope, (2) the A/R-scope, (3) the B-scope, and (4) the E-scope.

A-Scope Presentation

In A-scope presentation the x, or horizontal, axis represents range, and the y, or vertical, axis represents signal amplitude. The latter is indirectly used to obtain bearing, because signal amplitude is greatest when the antenna is pointing directly at the target. Figure 12-5 shows an A-scope presentation. The type-A scope, as you can see, displays echo amplitude against a time base which is calibrated to represent range. This presentation's usefulness is limited to showing slant range directly.

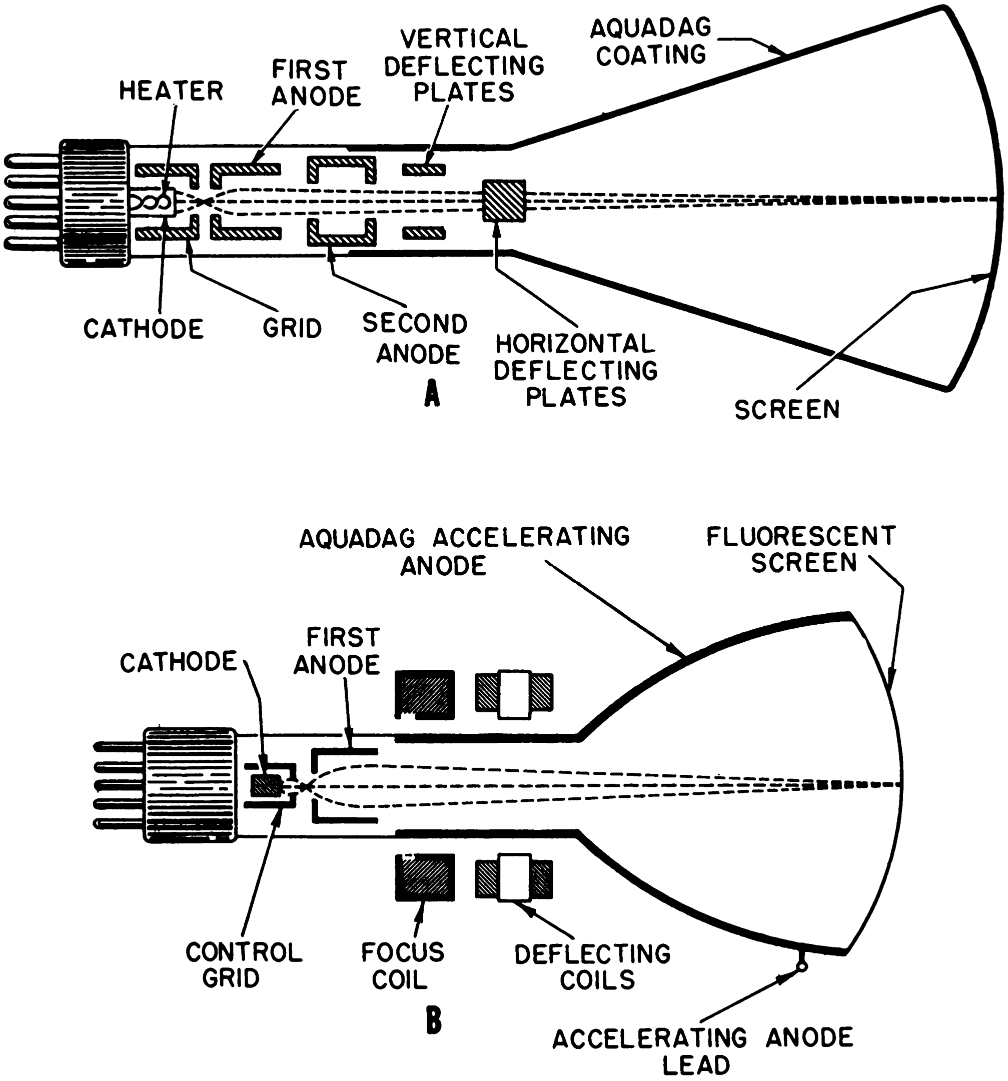


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Figure 12-4.—Cathode-ray tubes. A. Electrostatic; B. Electromagnetic.

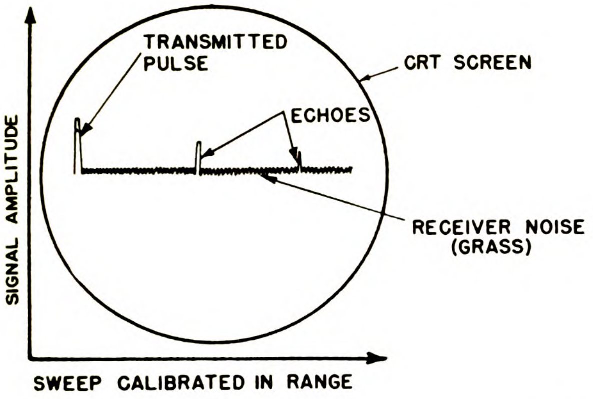

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Figure 12-5.—A scope presentation.

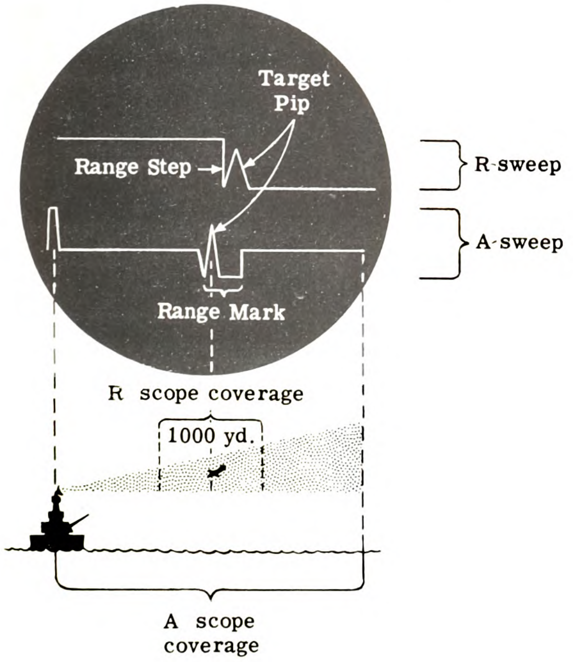

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Figure 12-6.—The A/R-scope.

A/R-Scope Presentation

Because the A-scope is unable to measure the target's range with a high degree of accuracy, the A/R type presentation is used. The A/R scope, (fig. 12-6) has a double-trace presentation. The lower trace (A-sweep) is similar to the A-scope presentation. A notch in the A-sweep, called a range mark, is movable and can be set on the target pip by the operator. The upper trace (R-sweep) is an expansion of that portion of the A-sweep representing several hundred yards either side of the range mark. Thus by adjusting the position of the range mark, the operator can examine any desired portion of the A-sweep on the expanded R-sweep. By adjusting the range mark's position the target pip can be brought exactly to the edge of the range step, which is simply a drop in the level of the R-sweep fixed at the center of the scope. Range can thus be very accurately measured on the calibrated control knobs.

B-Scope Presentation

In the B-scope presentation the picture seen is that of a narrow, wedge-shaped segment of space. Whenever the radar equipment picks up a target a bright spot appears on the scope in a position corresponding to the position of the target. The centerline or zero bearing line is aligned with the line of sight of the director. The distance between vertical lines represents intervals of about 3 degrees in bearing. Ranges are measured upward from the bottom of the scope by shifting the horizontal range line until it touches the bottom of the echo and reading the range on a calibrated dial. The exact bearing of a single target is obtained by training the director until the zero bearing line bisects the target, as shown in figure 12-7.

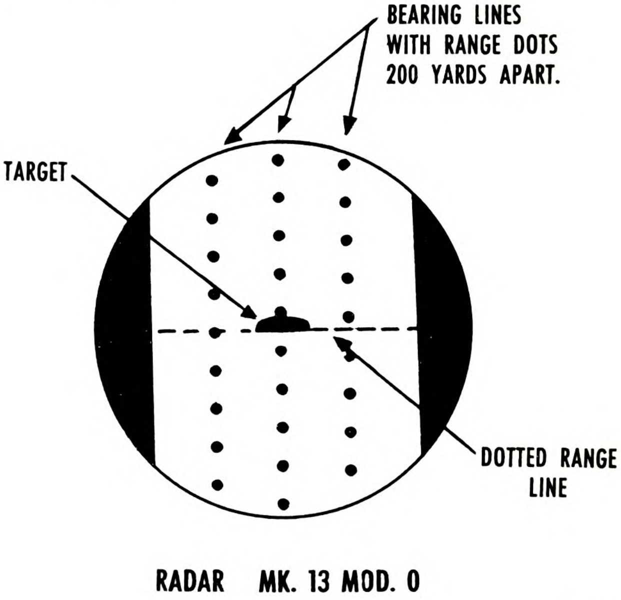

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Figure 12-7.—B-scope presentation, radar boresight axis on target in bearing.

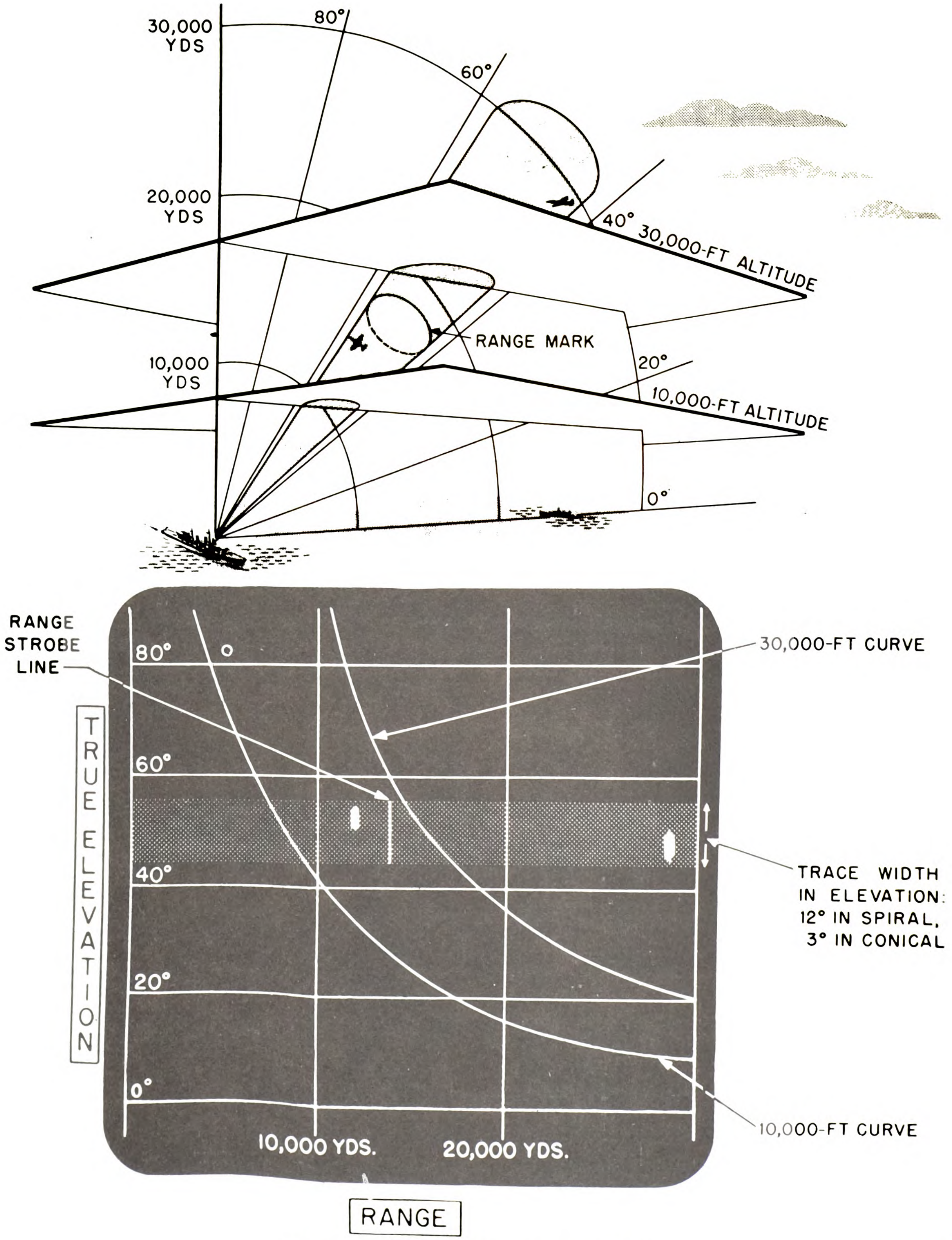

Figure 12-8.—E-scope presentation. 92.32

E-Scope Presentation

The type E-scope, shown in figure 12-8, is similar to the B-scope, except that it presents range horizontally and target elevation on the vertical scale. The target echo appears as a short vertical pip. The coverage or sweep of the radar beam is represented by a series of horizontal traces across the scope face between the elevation angles scanned by the radar beam. A vertical range mark is used in the same manner as the B-scope range line to measure range. Two curved lines on the scope face furnish an indication of target altitude. No measurement of target bearing is possible with this scope; it must therefore be obtained from a separate indicator such as a B-scope.

COMPARISON OF SEARCH AND FIRE CONTROL RADAR

There are two basic differences between search and fire control radar systems: the shape of the beam and the way it is moved, and the accuracy of the data obtained by the radar. The shape of radar beams varies considerably, depending on the radar system. In general, however, search radar beams are much broader and higher than fire control radar beams. The antenna of a search radar is rotated continuously through 360 degrees in order to scan the entire area around the ship. On the other hand, a fire control radar antenna, once it is aimed at the target, is moved only as necessary to track the target. The narrow beam of fire control radar, kept centered on the target, provides an accurate means of determining target position. Search radar cannot do this because the radar beam covers such a large area that it is impossible to tell the exact position of the target. In addition, the search antenna cannot be kept in one position to track a single target, since it must provide a continuous picture of the entire surrounding area.

CHAPTER 13

FIRE CONTROL PULSE RADAR

In this chapter we will discuss a pulse-modulated radar capable of automatically tracking a target. Tracking radars are almost universally pulse-modulated because of the superior ranging accuracy of this system. Automatic tracking radar, or "lock-on" radar as it is familiarly called, is an integral part of the target tracking system. We will first show how the radar fits into the tracking loop. After we have seen the tracking picture, we will discuss the radar itself.

TRACKING SYSTEM

The tracking loop of a dual purpose gun fire control system is shown in figure 13-1. The illustration is greatly simplified, but it will give you an idea of how the radar fits into the tracking picture. Briefly, this is the way the tracking system works.

When the director receives designation signals, it slews to the approximate position of the target. The director operators search for the target, watching their radar scopes for target echoes. Meanwhile the radar unit assembly, shown in the figure, is triggering the transmitter in the transmitter-receiver unit, which sends pulses of r-f energy to the antenna. When the antenna is on target, the received echo signals are fed to the radar unit assembly. The echo signals are amplified, and video signals extracted from the echoes are transmitted to the indicators and to the console.

When the target echo is in the range gate, the radar locks on the target and automatic tracking is started. Train and elevation data are supplied to the automatic tracker unit of the radar. The automatic tracker processes this information and provides the director with train and elevation correction signals to keep the radar beam on target. The fire control computer receives the train and elevation angles from the director, and range from the radar. Once the computer starts to track the target, it furnishes aided tracking signals to the director. In general, the aided tracking signals are derived by the computer from the motion of the tracking line. They are in parallel with the radar tracking signals and assist them in keeping the tracking line on target.

A pulse radar transmits r-f energy in small discrete packages. Each pulse represents a "look" at the area covered by the beam. Movement of the target is detected by comparing the echoes from subsequent pulses. Changes in target position cause variations in the echoes of the pulses. The variations in the echoes are used to sense the target's position with respect to the radar antenna's boresight axis. We will discuss the radar's tracking system under the functional sections of the radar.

FUNCTIONAL SECTIONS OF THE RADAR

There are many types of pulsed radars. Their physical arrangements are varied, and usually not interchangeable but their functional sections are compatible. Therefore, although we have selected a particular radar for our discussion, the information can be applied with only slight modifications to other pulse type radars. The pulse-Doppler radar, which is a special type of radar, will be covered in the next chapter.

Figure 13-2 shows a representative pulse radar broken down into functional blocks. A simplified data flow between the functional systems is shown. The first step toward understanding the theory of operation of a pulse radar is to firmly grasp the sequence of its timing system. The synchronizing or timing system is the "nerve network" of the radar.

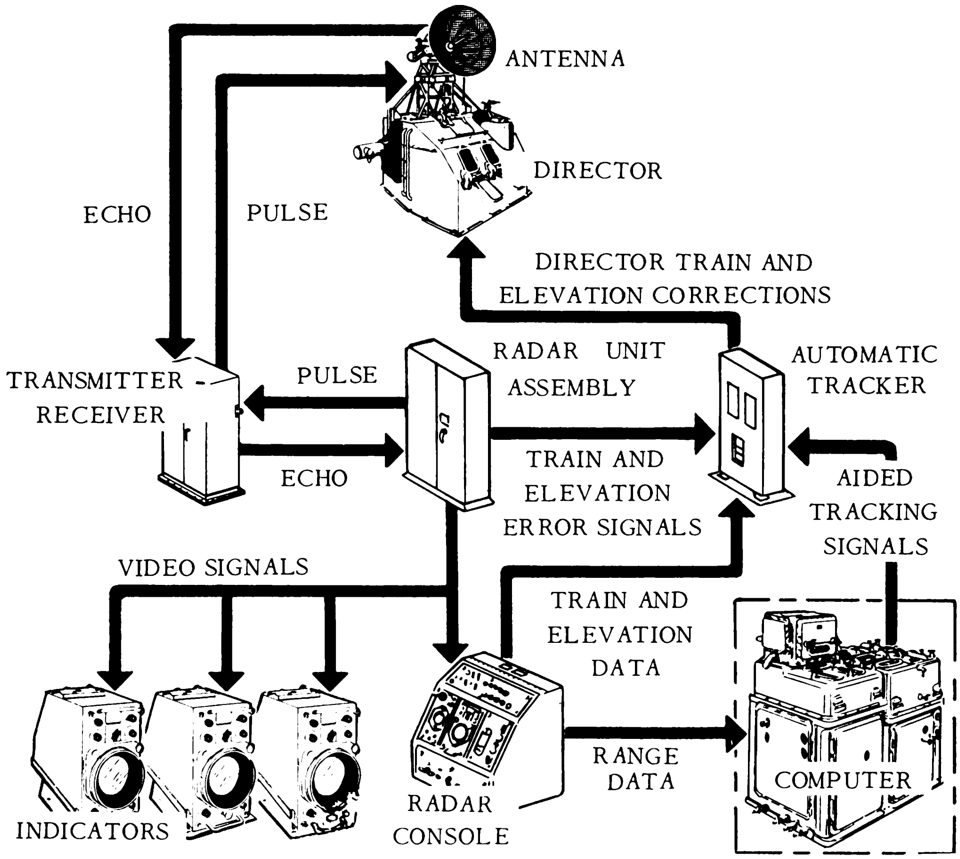

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Figure 13-1.—The tracking system.

SYNCHRONIZER SYSTEM

The synchronizer establishes a time reference for the radar; that is, it sets up the order in which the units of the radar operate. The pulses produced by the synchronizer trigger the modulator, the receiver, the indicator, and the ranging and automatic tracking systems.

A radar determines range by measuring the elapsed time between the transmission of the r-f pulse and the reception of the echo. Therefore, time in the various functional systems must be correlated. Let's see how the synchronizer can measure time electronically and relate time to range.

Assume we have an oscillator circuit that will produce a sine-wave voltage with a frequency of 163.88 kilocycles per second. If the oscillator is highly stable the phase of the output wave will vary linearly with time. Therefore, the sine wave would take a definite amount of time to complete a cycle and there would be a fixed period of time between the positive peaks of the wave. It takes 6.1 microseconds to complete a cycle at this frequency, (actually it takes 6.18 microseconds, but we will call it 6.1). This is equal to the time it takes a radar pulse to travel to a target 1,000 yards away and return. Therefore, one cycle of the oscillator's output is equal, with respect to range, to 1,000 yards. Special shaping circuits distort the sine wave into spikes occurring at 6.1-microsecond intervals. The spikes are used as reference marks for the radar's timing system.

The reference marks are basic timing triggers essential to the operation of the entire radar. But the marks have not been related to a zero reference time. They are like the minute hand of a clock; we can measure the

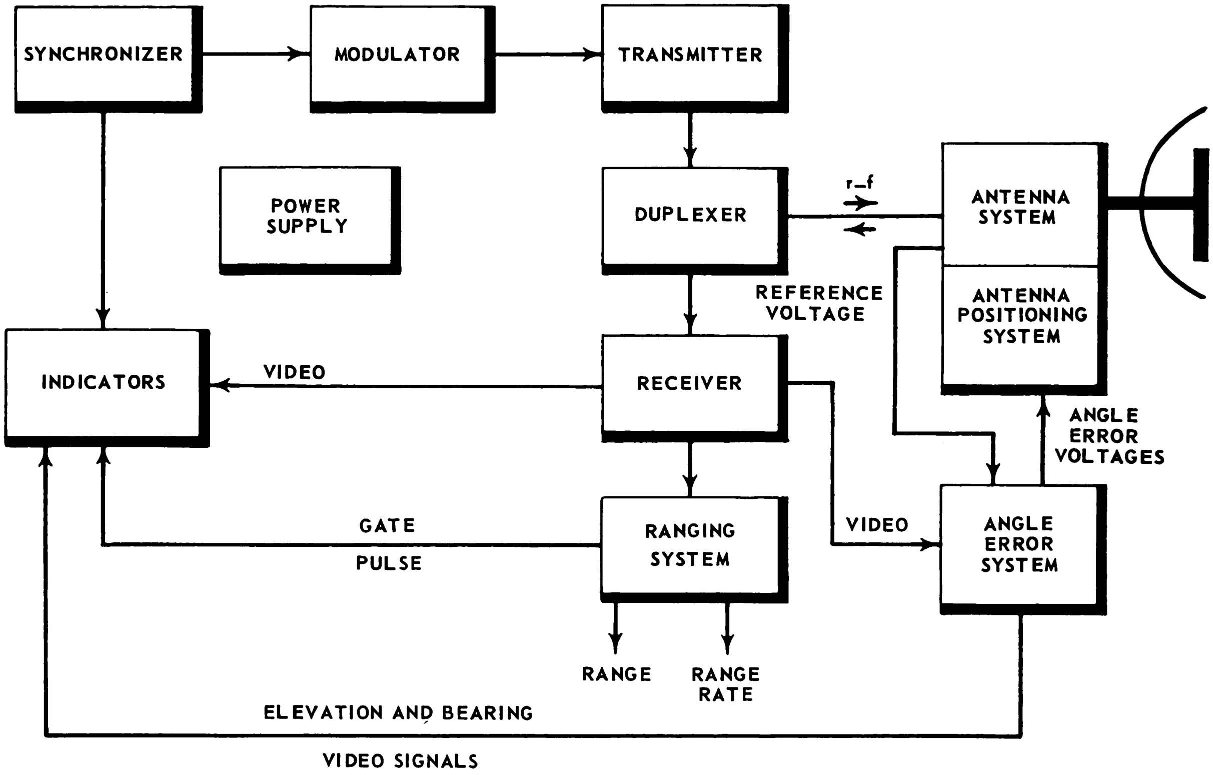

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Figure 13-2.—Functional block diagram of basic fire control radar set.

passage of time with it, but to be completely useful the hour hand is necessary to establish a reference point from which to start. The zero reference time in a radar is the instant of radiation which is determined by the radar's pulse repetition rate (PRR). Thus the reference marks must be correlated with the PRR for timing the operation of the units of the radar.

A second oscillator, which we will call the master oscillator, produces an output whose frequency corresponds to the PRR of the radar. The output of the master oscillator, when properly shaped, is the main timing pulse that determines the time of the radar's transmission. If the radar's PRR is 1,250 cycles per second we would have a main timing pulse every 800 microseconds. The frequency of the master oscillator's output must be stable if we are to obtain accurate and constant results. But the main timing oscillator is adjustable so that the radar's PRR may be changed.

In some installations a single master oscillator is used to time several radars. This is done to reduce the mutual interference between equipments that operate on nearly identical carrier frequencies, and to coordinate the operation of radar which must work in conjunction with one another. Most fire control radar can operate on either an internal or an external source of the main timing pulse.

The main timing pulse, (also called Modulator pulse), is the radar's reference point from which time is measured. Once the radar has started to operate, the time relationship between the reference marks and the main timing pulse remains constant. Thus, the two sets of pulses are referred to as fixed references in the radar's timing system. To show how we can electronically correlate the two sets of reference pulses so as to control the timing of the radar's units, we will first mention two special circuits: the coincidence amplifier and the blocking oscillator. The circuits will be covered in detail in the FT2 course.

Coincidence Amplifier

A coincidence amplifier is a tube and its associated circuits that requires the simultaneous application of two input pulses before an output pulse can occur. If only one of the inputs is present there will be no output. In other words, the tube is biased so that both inputs are needed to cause it to conduct, and the tube will conduct only so long as both are present.

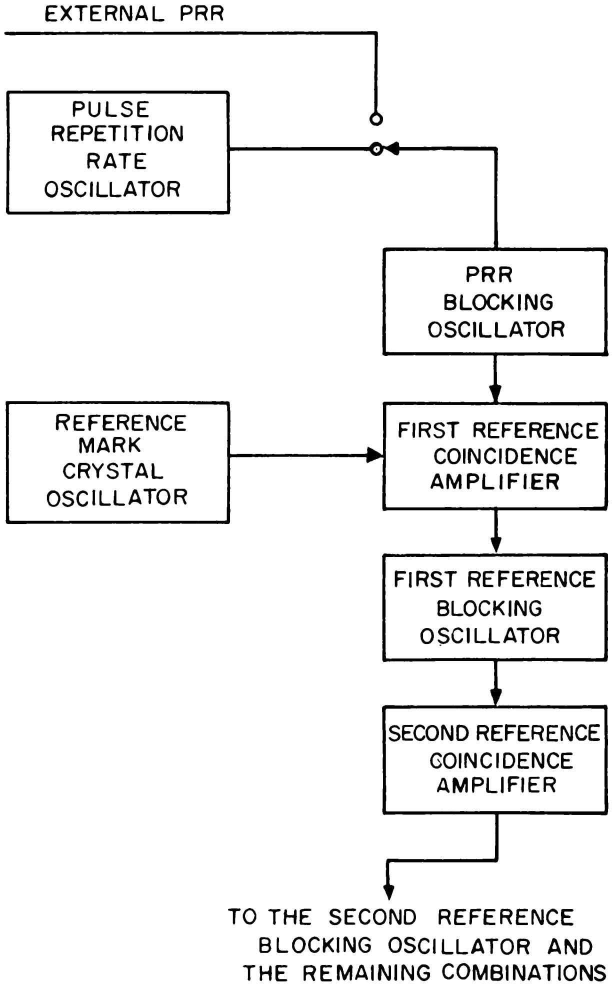
We will use the coincidence amplifier to correlate the two sets of timing pulses in the radar's synchronizer. A circuit that depends upon the output of a coincidence amplifier to start its operation will receive a signal pulse only when a reference mark and a master timing pulse are present in the amplifier.

Blocking Oscillator

There are two types of blocking oscillators: the triggered, and the free-running types. We are interested here in the triggered type. The blocking oscillator is a generating circuit. We use it to generate gating pulses with a definite duration and that reoccur at a specific frequency. The blocking oscillators and their associated circuits in the radar generate an 8-microsecond pulse when the oscillator is triggered by a timing pulse.

Now let's apply this information to the synchronizer system. Since the radar measures range as a linear function of time, the units of the radar must vary linearly with time. Many of the units do not have this feature throughout their operational limits. For example, some radar indicators need a short interval in which to start their trace and become linear. Hence it is necessary for the synchronizer system to produce triggers that are separated by the time the units need to begin linear operation. But zero range must be coincident in time with the r-f energy leaving the antenna. The modulator trigger to the transmitter is delayed a sufficient amount of time so that all the units are in their linear portion of operation and are aligned to zero range when the r-f energy leaves the antenna.

Figure 13-3 shows a simplified block diagram of the synchronizer system. As shown, the PRR pulse can originate externally, or internally from the PRR oscillator. The PRR pulse is fed into a blocking oscillator whose output is an 8-microsecond positive pulse. This pulse is applied to the first coincidence amplifier. The other input to the amplifier is the 6.1-microsecond reference mark from the crystal oscillator. The coincidence amplifier will conduct only when both inputs are present. Since the PRR blocking oscillator pulse is 8 microseconds long, at least one of the reference marks will occur while it is present.


EXTERNAL PRR
PULSE REPETITION RATE OSCILLATOR
PRR BLOCKING OSCILLATOR
REFERENCE MARK CRYSTAL OSCILLATOR
FIRST REFERENCE COINCIDENCE AMPLIFIER
FIRST REFERENCE BLOCKING OSCILLATOR
SECOND REFERENCE COINCIDENCE AMPLIFIER
TO THE SECOND REFERENCE BLOCKING OSCILLATOR AND THE REMAINING COMBINATIONS

12.313

Figure 13-3.—Simplified block diagram of a synchronizer system.

In the first coincidence amplifier we have established a relationship between when we want the radar to transmit and the reference marks which are used to measure time and range in the radar. The output of the coincidence amplifier is fed into the first blocking oscillator whose output is an 8-microsecond pulse. This pulse is applied to the second coincidence amplifier. The other input to the amplifier is the reference marks. When both inputs are present the amplifier will conduct; this conduction is exactly 6.1 microseconds after the first coincidence amplifier conducted. The combination of coincidence amplifiers and blocking oscillators will provide delays in multiples of 6.1 microseconds. Radars that require linger delays have more of the combinations in series.

Figure 13-4 is a timing chart that shows the sequence in which the triggers are developed. The reference marks and the PRR gate are the initial timing control signals. Notice the 6.1-microseconds delay between the outputs of the blocking oscillators. The "A" trigger, also called the sync pulse, is an output of the synchronizer that is used to start the "A" sweeps in the indicators and circuits in the receiving, ranging, and tracking systems. The functions of the A trigger will be covered when we discuss the other functional blocks of the radar.

The r-f energy in the radar's transmitter is generated in response to the modulator trigger (mod trigger) output of the synchronizer. Notice that the mod trigger is developed 2,000 yards after the A trigger. This is the delay in this radar, but each radar has its own timing chart. Notice that range in yards is used interchangeably with time in microseconds.

Refer back to figure 13-2, the block diagram of the radar. We will continue our discussion of the radar by following the mod trigger from the synchronizer system to the transmitter.

TRANSMITTER

The radar transmitter is made up of two functional sections—the modulator and the r-f oscillator. The modulator contains the circuits that generate and shape the high-power d-c pulse that is applied to the r-f oscillator. The oscillator is a magnetron oscillator that generates the superhigh carrier frequency of the radar. Now let us take a closer look at these two sections to see how they operate.

The Modulator

Suppose we follow the modulator, (fig. 13-5), through one pulse cycle. The radar is receiving at the start of the cycle. The switching device would be open and therefore the circuit between the pulse-forming network (PFN) and the pulse transformer would be open. While the switch is open the PFN will charge from the d-c power supply through the charging choke. The charging choke is an inductive coil that forms a resonant circuit with the PFN. The flow of current through the choke produces a voltage that continues to charge the PFN after it has reached the level of the power supply voltage and the PFN becomes charged to about twice the value of the supply voltage.

When the PFN reaches its maximum charge, it is ready to be switched, or keyed. In other words, the network is ready to be discharged through the load to ground. The exact time that the PFN is switched is determined by the mod trigger.

When the switch closes, the PFN discharges at a rate determined by the LC constants in the network. The resulting high amplitude d-c pulse is applied through the primary of the pulse transformer. The sudden pulse in the transformer primary induces a pulse of extremely high voltage in the secondary. The secondary winding is connected to the cathode of the r-f oscillator. The powerful negative pulse at the cathode of the magnetron causes it to oscillate for the duration of the pulse.

THYRATRON SWITCH.—The switching device is a thyratron tube. Thyratron tubes are covered in Basic Electronics, NavPers 10087-A. It is easy to see from its operational characteristics why this type tube is used as the switch. The thyratron's switching action is very rapid. It goes from practically infinite resistance (switch open), to nearly zero resistance (switch closed), almost instantaneously. Current through the tube rises and drops off in almost a straight line. The modulator's output pulse has a rectangular waveshape.

A negative bias on the thyratron's grid keeps the tube from conducting while the PFN is charging. In other words, the switch is open. The switch is closed by the positive mod trigger. The tube will conduct until the plate potential falls below the tube's cutoff valve. When this happens the PFN is discharged and conduction through the tube stops. Control of the tube is returned to the grid and the PFN starts to charge in preparation for the next cycle.

The Magnetron Oscillator

The second functional section of the transmitter is the magnetron oscillator. The magnetron tube used in fire control radars is similar in operation to the one discussed in Basic Electronics, NavPers 10087-A.

The plate of the magnetron oscillator is grounded. The pulse from the modulator is applied to the cathode. This negative pulse provides the plate-to-cathode potential necessary for the tube to conduct. Since the modulator's pulse has a rectangular shape, the magnetron

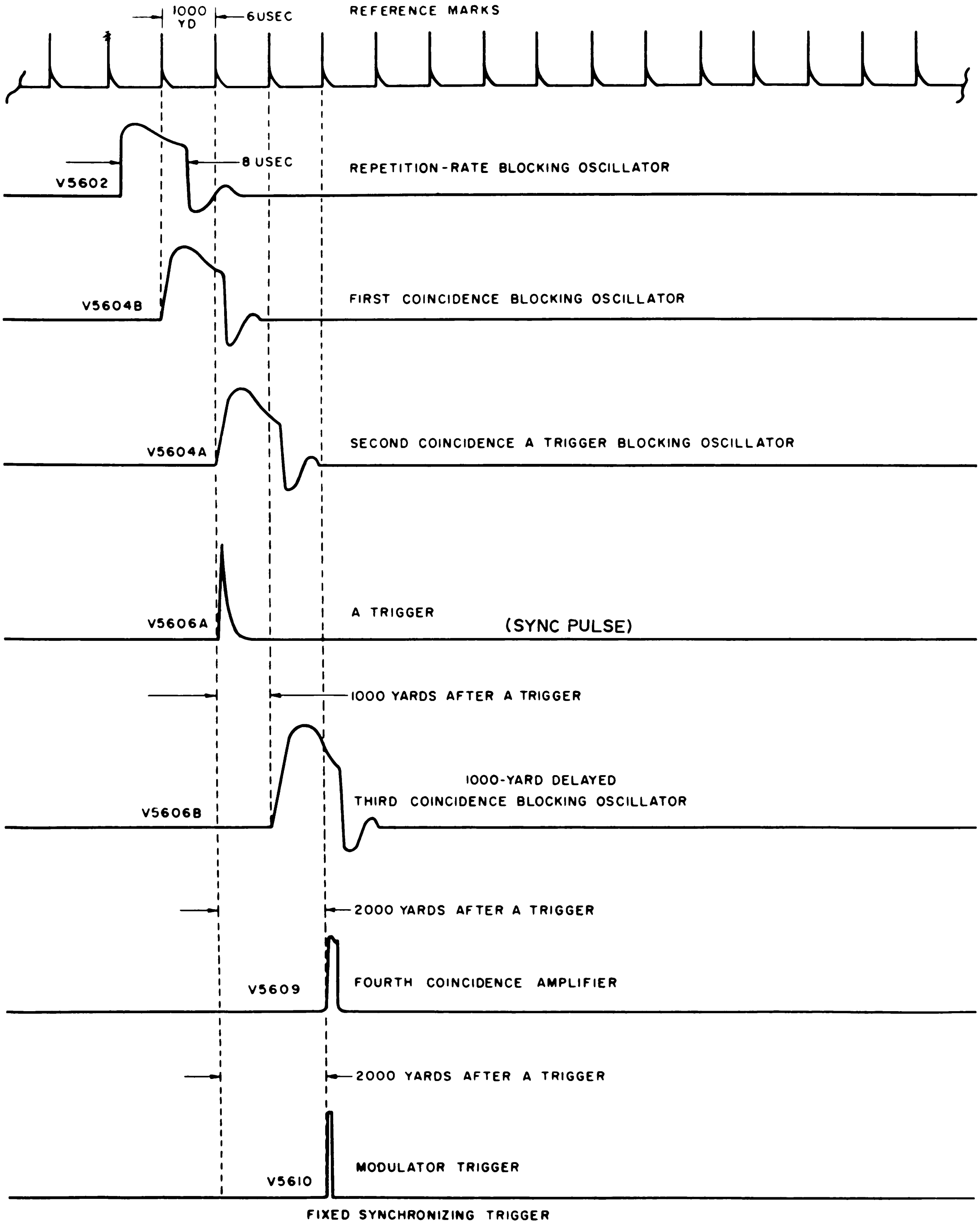


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Figure 13-4.—Radar's timing chart.

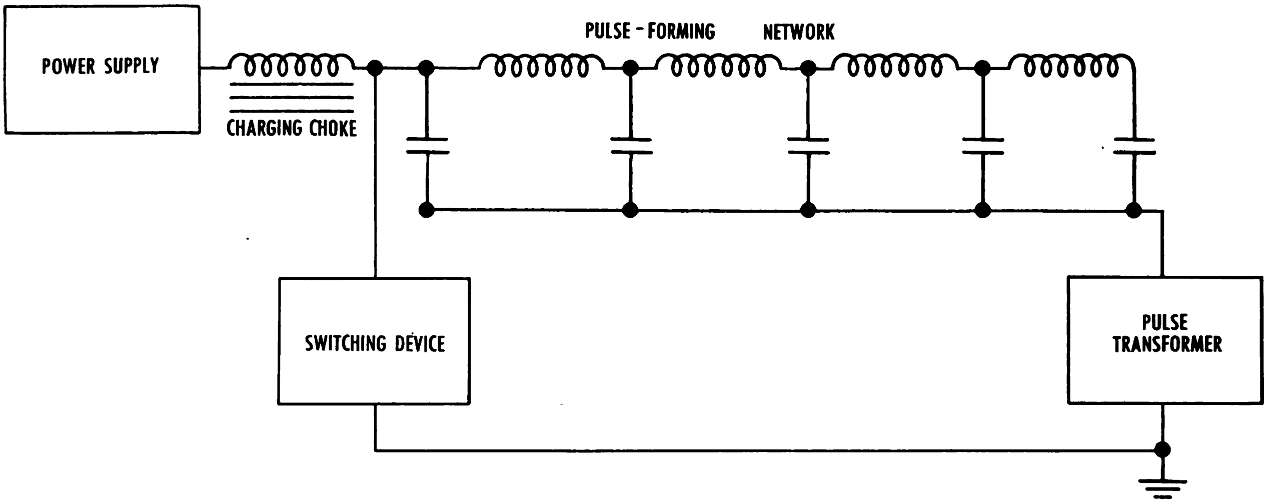

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Figure 13-5.—Simplified diagram of themodulator.

starts to oscillate at the proper frequency and continues to oscillate at this frequency for the duration of the pulse.

The magnetron's magnetic field is produced by a permanent magnet. The r-f oscillations set up in the cavities of the magnetron's plate are coupled out by a loop-coupling probe extending into one of the cavities. The r-f oscillations are coupled into the transmission line, which carries them to the antenna.

Magnetrons are inclined to stray from their proper frequency. Normally this straying does not affect the radar's operation because the automatic frequency control in the receiver adjusts the local oscillator to compensate for the frequency drift in the magnetron. Sometimes, however, it is desirable to hold the transmitter on a certain frequency, or to vary the frequency from time to time. The magnetron in the radar can be tuned over a range of about ten percent of its frequency band. Hence the radar's carrier frequency can be changed to obtain the best operation, to get off a frequency being jammed, or to match the radio frequency of a beacon.

TRANSMISSION LINES

The carrier frequency of fire control radar is in the superhigh-frequency band, well within the microwave region. Although electrical energy at microwave frequency obeys the fundamental laws of electricity, its behavior is unique. The ordinary two-wire transmission line is inefficient at these frequencies and waveguides or coaxial lines are used. We will leave the theory of waveguides and coaxial lines to a later course, and confine this discussion to some general statements about r-f transmission lines. The statements will help us to understand the overall operation of the radar and the operation of the duplexer and the antenna feeder system (fig. 13-2) in particular.

The high p-ower r-f pulse from the magnetron is coupled into the waveguide. The waveguide, in turn leads to the antenna. You may think that delivering the r-f pulse to the antenna is a simple matter, but it is not. First of all, when r-f energy is coupled into or out of a waveguide the impedance of all the elements involved must be matched in order to obtain a maximum transfer of energy. If the impedance is not properly matched some of the r-f energy will be reflected back toward its source. This will create standing waves. A standing wave is produced by two waves traveling in opposite directions and having the same frequency, such as an incident wave and its reflected wave from a mismatch. Standing waves represent wasted power in the radar.

The transmission line should have a characteristic impedance that is equal to the antenna's impedance. The antenna is the load on the line. Where this occurs, all the power will be absorbed by the antenna and none will be reflected back into the line. But as you know, there is a marked change in impedance with a change in frequency. The r-f generator (the magnetron oscillator), has a tendency to drift slightly in frequency and its frequency is tunable. Therefore, impedance-matching devices are included in the waveguide. The impedance of the transmission line is adjusted to match the impedance of the generator, the line, and the load.

The design of the transmission line is further complicated by the fact the antenna is used for both transmitting and receiving. Consequently, the r-f line from the antenna must be connected to the transmitter and to the receiver. If the receiver is not protected from the powerful r-f pulse when the radar is transmitting, crystals in the receiver's mixer assembly would be destroyed, however, the receiver must be sensitive enough to respond to very weak echo signals. When the radar is receiving, we cannot afford to lose some of the echo signal by having it travel down the branch of the r-f line going to the magnetron. This would result in weaker targets not being detected.

Duplexer

A switch could be used to shift the r-f line between the transmitter and the receiver, but it would have to be a special switch. The operation of the switch must be synchronized with the PRR of the radar so that the proper channel is blocked at the proper time. Since the PRR of fire control radars is over 1,000 cycles per second, an electromechanical switch is impractical.

The switching device that makes it possible for the transmitter and the receiver to use the same antenna is called a duplexer. The duplexer consists of sections of waveguide and TR tubes. It is the TR tubes that provide the fast switching action of the duplexer.

THE TR TUBE.—A TR tube (fig. 13-6) is a special gas tube with a spark-gap. A spark-gap is a gap between two electrodes across which a potential difference may exist. If the potential difference is high enough, the tube will fire, producing a short across the gap. The operation of a TR tube is comparable to the operation of the common neon lamp used in the fire control switchboard. The width of the gap determines the potential difference needed to cause the tube to fire. In the radar the transmitted r-f energy will cause the tube to fire. Normal returned r-f signals however, are too weak to cause the tube to fire.

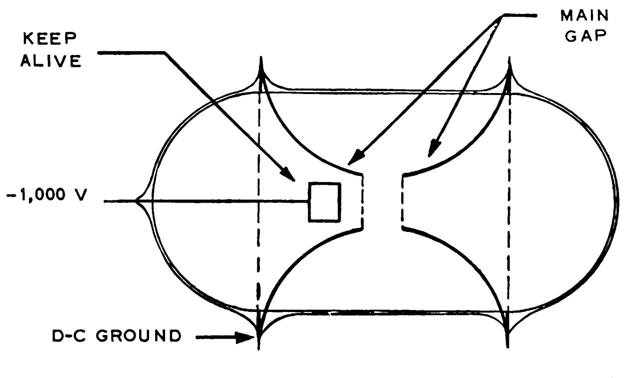

Figure 13-6.—TR tube with keep-alive electrode. 55.106

Figure 13-7 shows a simple duplexer with a single TR tube in the branch of the waveguide going to the receiver. When the magnetron oscillates it produces high power r-f energy. The transmitter's r-f energy causes the TR tube to conduct and short out across the waveguide to the receiver. The short circuit protects the receiver from the transmitted pulse by effectively closing this branch to all r-f energy except that necessary to keep the TR tube firing. But before the tube can fire, a small amount of the r-f energy enters the receiver. It is this r-f energy that produces the transmitter pulse that is seen on the radar indicators. To limit the amount of r-f energy allowed to enter the receiver before the TR tube fires, a high negative potential is applied to one of the tube's electrodes. This voltage is called the "keep-alive" voltage and is used to maintain the gas in the tube in a state of partial ionization. Thus a short is produced more quickly when transmission is started.

THE ATR TUBE.—When the magnetron stops oscillating, the short across the TR tube is removed and the duplexer is returned to its

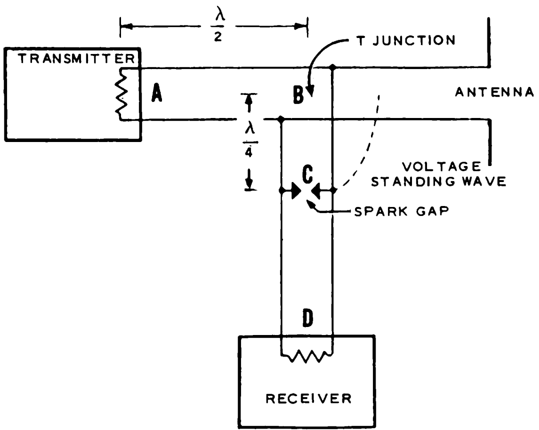

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Figure 13-7.—R-f system using a TR tube.

receive position with the receiver branch of the waveguide open to the antenna. In the simple duplexer shown in figure 13-7 the transmitter has not been disconnected from the antenna and some of the returned r-f energy could enter the transmitter. To insure that all the returned energy enters the receiver, a second tube called the ATR (anti-TR), is used. This tube is located in a waveguide branch connected to the main line between the transmitter and the receiver (fig. 13-8).

The ATR tube operates in the same manner as the TR tube. The r-f energy from the transmitter shoots the gap and fires the tube. The shorted ATR tube closes the branch from the r-f energy. When the magnetron stops oscillating the short across the ATR tube is removed. The ATR waveguide branch is a critical length shorted at its end. This short presents a very high impedance to the returned r-f energy traveling down the waveguide towards the transmitter. The high impedance effectively closes the path to the transmitter for the returned r-f energy, and it all goes into the receiver.

The Antenna

The purpose of the antenna is to radiate the r-f energy from the transmitter into space and to receive the reflected energy from space. The radar we are discussing has a parabolic reflector. We described the characteristics of this type antenna in chapter 12. That discussion plus the coverage of radar antennas in the Basic Electronic course, NavPers 10087-A, is sufficient for our purposes at this time.

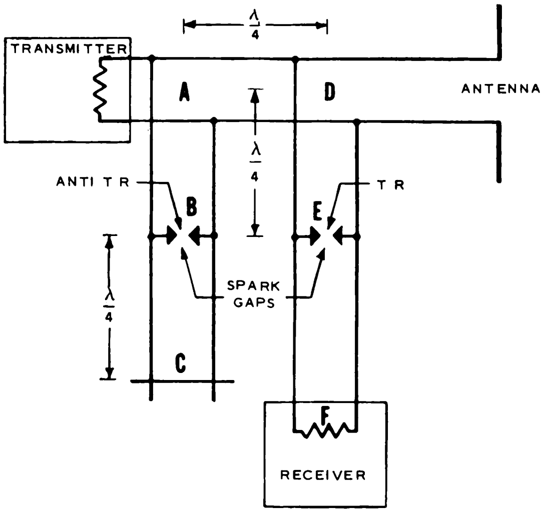

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Figure 13-8.—R-f line with TR and ATR tubes.

CONICAL SCANNING.—Most fire control radars scan the target area by deflecting the radar beam about the centerline axis of the radar antenna. The beam is moved in a regular motion to cover a definite amount of space. There are many types of scans, each has its own scan pattern. One of the most common types is conical scan, where the beam is moved in a circle. We will describe this type of scan; the other types are similar in principle.

First let's consider a radar without a scanning system. The radiated r-f energy is concentrated by the antenna's reflector to form a narrow beam. Once the radar is on target, this type beam pattern is ideal for establishing target position. But it is very difficult to acquire the target because of the narrow beam. Furthermore, when the target is in the beam we would receive an echo but no indication of target motion. We could wait till the target's motion carried it out of the beam, then bring the beam back on. The direction and amount we moved the antenna could then be used as an indication of targets' motion. Obviously this would not be very satisfactory.

Fire control radar has a high PRR and can "look" at the area surrounding a target over a thousand times per second. The radar takes advantage of this feature and moves the beam in a systematic pattern about the target area. This is called scanning. The radar compares the echoes from the pulses to detect any change in the target's position with respect to the center of the area scanned by the beam. Since a target cannot move very far in the short period of time between the radar pulses a smooth flow of tracking information is obtained.

In conical scan the radiated beam is deflected by the antenna to produce a rapidly rotating beam that forms a small cone. The apex (point or tip) of the cone is located at the center of the antenna as shown in figure 13-9. Conical scanning is accomplished by nutating the feedhorn while the reflector remains fixed. The reflector dish is in the center of nutation. This assembly is shown in figure 13-10. As a result of the nutation of the feed, the beam spins in space in the manner indicated in the figure.

Also shown in figure 3-10, during automatic tracking the beam points at an angle of a few degrees with respect to the antenna axis. A target located exactly on the antenna axis continuously receives a constant amount of the radiation, in this case about 80 percent of it. However, a target situated away from the axis

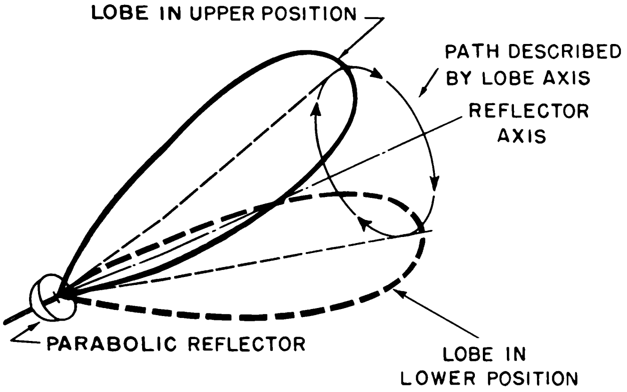

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Figure 13-9.—Conical scanning.

receives radiation that varies in strength from 100 percent of maximum to less than 30 percent, depending on its displacement from the line along which the antenna is pointing. This is shown more clearly in figure 13-11, in which the return signals from a target that is 1 1/2° off the antenna axis (fig. 13-11A) are contrasted with the echoes from a target on the axis (fig. 13-11B.)

The axis of the antenna does not change appreciably during the time required for several spins of the beam; hence the direction of the lobe after one-half revolution changes from the upper position shown in figure 13-11 to that shown in the lower position. As the beam rotates between these extreme positions, the echo signals vary gradually in strength, as shown in figure 13-12 so that the returned pulses are amplitude modulated in proportion to the displacement of the target from the antenna axis. The figure shows only eight echo signals per revolution for convenience, but in an actual case many more are present, the number for each revolution being determined by the ratio of the pulse repetition frequency to the rate of rotation of the beam.

The train and elevation angles of the target with respect to the antenna axis are indicated by the phase of the variations in returned signal strength, as indicated in figure 13-12. In A of the figure the signal is shown resulting from an

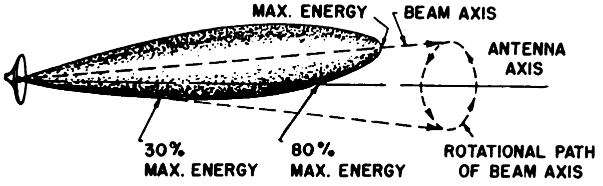

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Figure 13-10.—Antenna beam with conical scan.

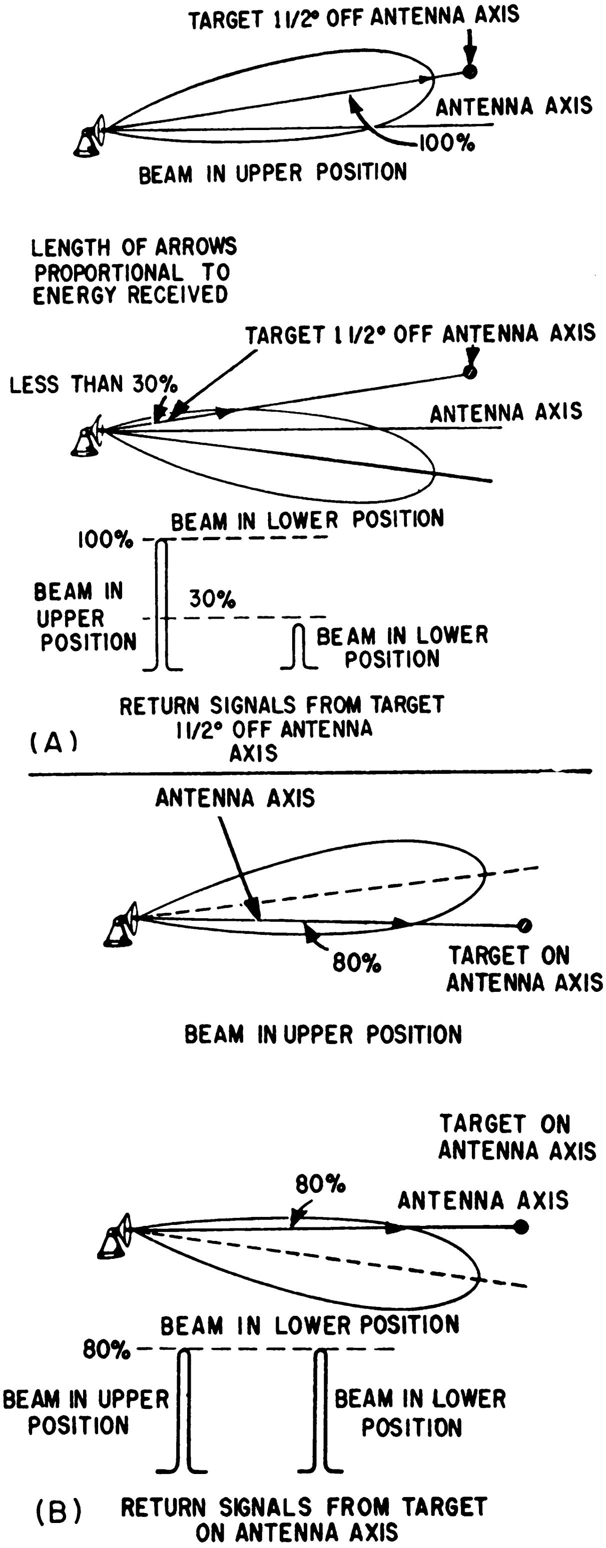

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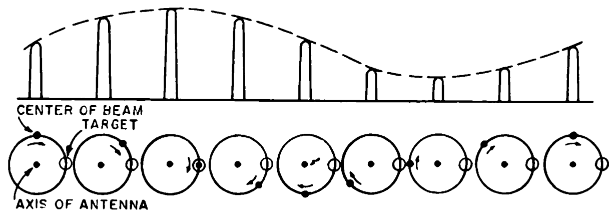
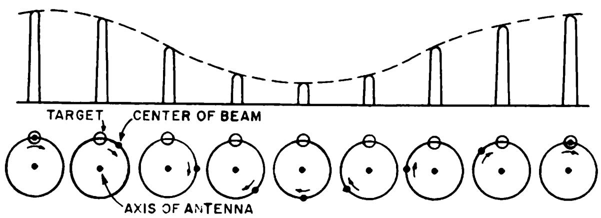
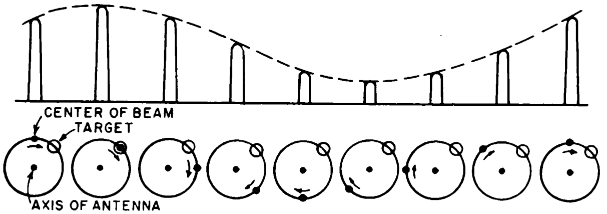
Figure 13-11.—Echo signals with conical scan.



A. SHOWING PURE TRAIN ERROR AND RESULTING SINE WAVE



B. SHOWING PURE ELEVATION ERROR AND RESULTING SINE WAVE



C. SHOWING ERROR IN BOTH TRAIN AND ELEVATION, AND RESULTING SINE WAVE

55.67

Figure 13-12.—Signals produced by bearing and elevation errors.

error in train only; while that produced by an error in elevation alone is shown in B. By comparing the two diagrams, it can be seen that the variation representing train error is displaced in phase by 90° from a signal produced by a pure elevation error. The error signal resulting from a combination of train and elevation errors is shown in C of the figure, in which the variation in amplitude reaches a maximum value somewhere between the moments of maximum for pure train or pure elevation errors. Any other position of the target off the axis of the antenna results in a similar error signal, the phase of which is determined by the direction of the train and elevation errors present. When the axis of the antenna points directly at the target, the echo pulses are all of equal amplitude, (fig. 13-11B).

The axis of the antenna is the tracking line or line of sight. The feedhorn is nutated at the scan rate about the line of sight by the scan motor. Therefore the position of the feedhorn with respect to the tracking line is determined by the scan motor's rotation. This motor also drives a two-phase reference generator whose outputs are two sine wave voltages exactly 90° apart. The generator's outputs are used as reference voltages to indicate the feedhorn position with respect to the antenna's train and elevation axes which, as you know, are 90° apart.

In automatic tracking the echo signals which are modulated at the scan rate and the reference voltages are applied to the train and elevation servosystems. Each system compares the phase of the modulated echo signals (sometimes called the video envelope), with the phase of its reference voltage and detects the error voltage. The train and elevation error voltages are used to control the position of the antenna so as to keep in on target.

RADAR RECEIVER

The effectiveness of a radar is perhaps determined more by the efficiency of its receiver than by any other single factor. The transmitter's job is simple in comparison. The transmitter operates as a source of high-power energy but the receiver must accept very small signals and process them. The receiver must detect the weak echo signals, amplify them to a useful level, and extract the information needed by the fire control system for target tracking. As if this job isn't hard enough, the receiver is further handicapped by the superhigh carrier frequency. In order to process the echoes the receiver must first reduce the carrier frequency to an intermediate frequency (i-f).

The receiver is an extremely sensitive superheterodyne receiver. A block diagram of the radar receiver is shown in figure 13-13.

Briefly, here is how the receiver works. At the very high frequencies used in radar, r-f amplification is usually impractical. The weak echo signal from the antenna generally is coupled directly into the mixer without previous amplification. In the mixer, the incoming signal is heterodyned with a signal from the local oscillator. The output of the mixer is therefore an intermediate, or difference, frequency.

The intermediate-frequency signal is then coupled through several stages of i-f amplification, where it is amplified many times. Numerous stages are needed because the wide bandwidth of each state limits its gain. The output of the i-f amplifier is fed to a detector, which rectifies the signal. The detector output is a positive or a negative video pulse envelope.

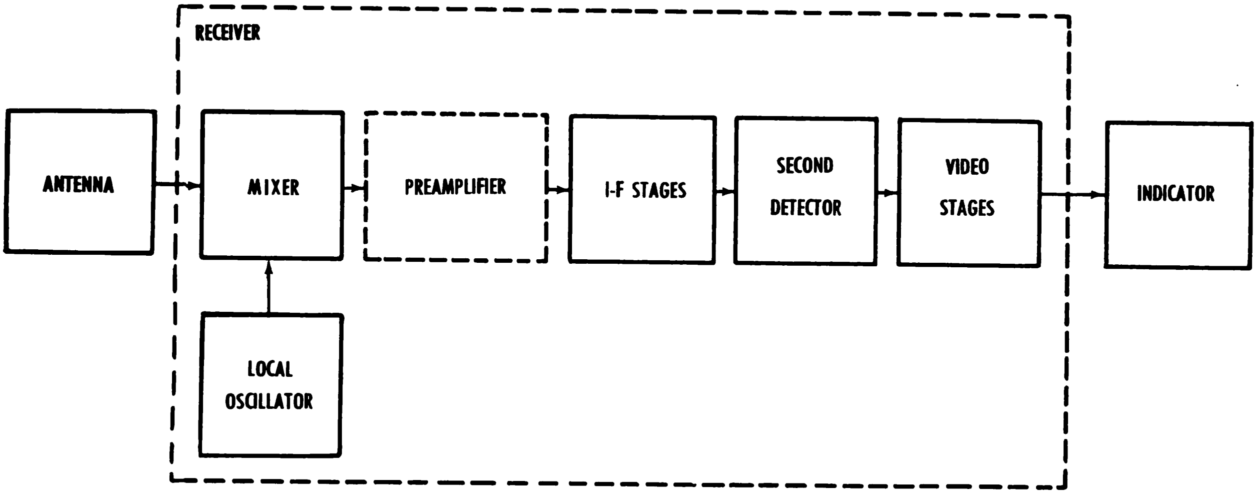


Figure 13-13.—Block diagram of a radar receiver. 55.112

The pulse envelope is fed to the video amplifier, which amplifies the signal for presentation on the indicator scope.

The mixer, local oscillator, and, in some radars, one or two i-f amplifiers are located as close as possible to the antenna to avoid the losses of a long r-f line to the receiver. When the first i-f amplifier stages are located near the antenna, the separate unit that contains them is called a PREAMPLIFIER. The output of the preamplifier is fed directly into the remaining i-f stages, and the order of operation is like that described in the preceding paragraph.

The echo signals are first detected by the receiver in the mixer assembly. That is why the detector block in the diagram is called the second detector. We will work our way through the receiver by following an echo signal's path. We will assume the magnetron has stopped oscillating and the duplexer has shifted to its receive position.

The Mixer

The mixer beats the echo signal input from the antenna with the output of the local oscillator to reproduce the echo signal at the intermediate frequency. For example, assume that the radar's carrier frequency is 9,000 megacycles and the local oscillator's frequency is 9,060 megacycles. When an echo is received and the two frequencies are beat—heterodyned, the difference or intermediate frequency is 60 megacycles. In some fire control radars the intermediate frequency is 30 megacycles per second.

Converting the radio frequency to a usable intermediate frequency is referred to as conversion, and is performed by rectifying crystal diodes. The operation of a crystal diode is explained in the basic electronics course.

The radar uses a balanced mixer located in the receiver's waveguide assembly. The balanced mixer consists of two crystal diodes and their waveguide sections. This arrangement is used to produce a maximum output signal with a minimum of the noise generated in the local oscillator. The inputs to the mixer (fig. 13-14), are the received radio frequency and the local oscillator radio frequency. Its outputs are the two input frequencies plus their sum and difference frequencies. The i-f amplifier is tuned to the difference frequency and the other frequencies are rejected.

The frequency of the magnetron oscillator and the local oscillator will change occasionally. A change in the frequency of either oscillator will change the intermediate frequency output of the mixer. A change in the intermediate frequency will reduce the efficiency of the receiver, and weak target echoes may not be detected. Therefore, the radar has an automatic frequency control (AFC) system.

The radar has a second balanced mixer called the AFC mixer. It operates the same as the receiver mixer except that the inputs to the AFC mixer are a sample of the transmitter r-f oscillator's output and the signal from the local oscillator. Its output is the intermediate frequency which is fed to a discriminator circuit. The discriminator detects changes in the intermediate frequency and produces an output voltage

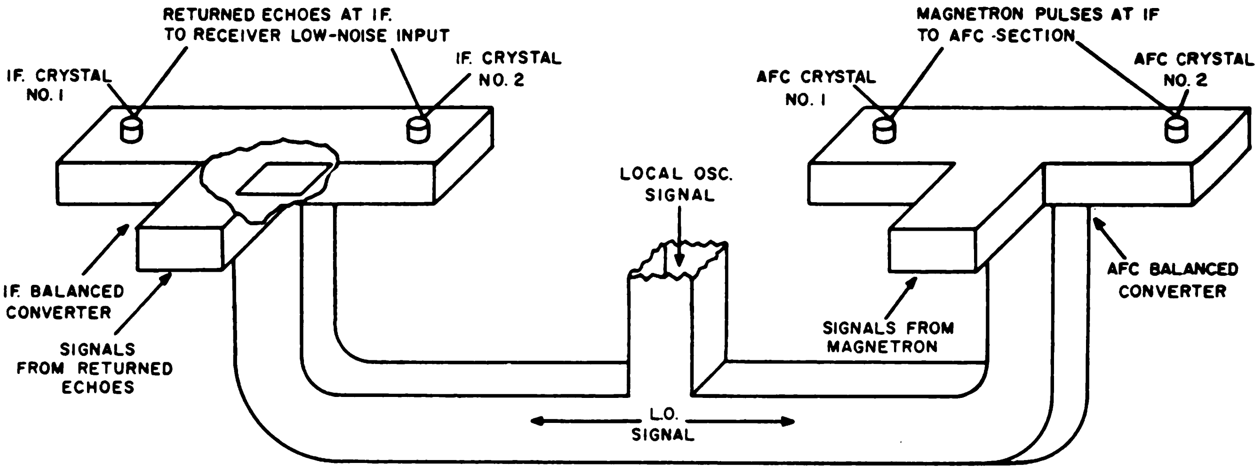


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Figure 13-14.—Balanced converters.

proportional to the change. This voltage is applied to the local oscillator to change its output frequency by the amount necessary to produce the correct intermediate frequency.

The Local Oscillator

The local oscillator is a klystron tube capable of producing a superhigh-frequency output. The klystron type local oscillator does not use an ordinary tube circuit as such, its tuned circuit is built into the tube structure and in physical appreance resembles a cavity enclosed by metal. Its output frequency is controlled primarily by the mechanical tuning of the cavity type structure. It can be controlled over a smaller range by varying the plate voltage which in this tube is called the repeller voltage. This voltage is varied by the voltage from the AFC circuit so that the frequency of the local oscillator follows the magnetron oscillator.

I-F Amplifiers

As you have already learned, the radar receiver is a superheterodyne type. The heterodyne action has taken place in the black blocks in figure 13-15. The AFC circuits, (not shown) automatically maintain the intermediate frequency at 60 megacycles. The i-f amplifiers must amplify the weak echo signals to a usable level.

The noise contained in the echo reflection received by the antenna is still present in the input to the i-f amplifiers. At this time, we still cannot be sure which part of the echo is actually noise and which part is in fact a true target echo. Therefore, the i-f amplifiers are tuned to amplify a broad band of frequencies centered at the intermediate frequency. To achieve this tuning, either one or two resonant circuits are used to couple the stages of the amplifiers.

The r-f energy reflected from the target back to the radar is very weak. The major part of the receiver's gain is obtained in the i-f amplifier. Gain control circuits in the i-f amplifier are used to adjust the sensitivity of the receiver to the existing conditions. The gain of the receiver can be controlled either manually or automatically. Manual gain is normally used when searching for a target and is a straight-forward gain system. Automatic gain control (AGC) is used for normal tracking and varies the gain of the i-f amplifiers with the power level of the gated video signal. But the automatic gain control system has unique features to compensate for special conditions that may be present at the target and in the receiver. We will consider these features later when we discuss electronic countermeasures.

The output of the i-f amplifiers goes to the detector (fig. 13-15). The detector rectifies the i-f signals and produces an output voltage proportional to its input. The output voltage is the video signal. This signal is fed to the video amplifier where it is amplified and then supplied to the radar indicators for visual display. The amplified video signal is also used to generate the range error voltage in the radar's tracking system.

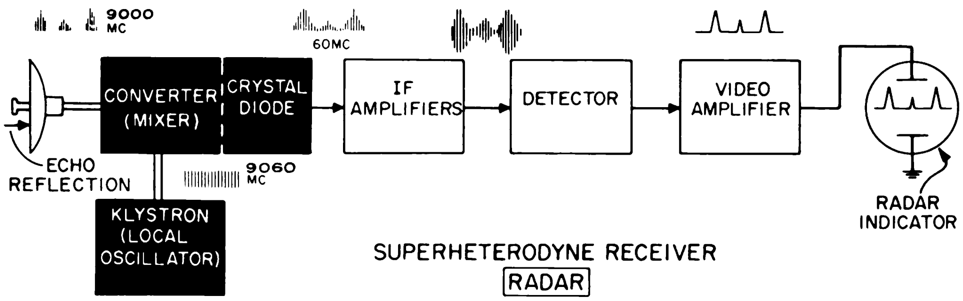

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Figure 13-15.—Radar receiver.

RANGE SYSTEM

We have extracted the video signals from the returned echoes and sent the signals to the indicators. Now we must determine the range to the target. Range is determined by measuring the time delay between the transmission of the transmitted pulse and the reception of the echo from the target. The time delay is, of course, variable; its length depends on target range. Therefore, the circuits which produce the time delay must be capable of measuring a variable delay. Moreover, the time delay must be measured precisely since range is a very important factor.

We are again using the terms "time" and "range" interchangeably. There is a linear relationship between time and range in the radar; 6.1 microseconds equals 1,000 yards.

The range system can be divided into a coarse and a fine delay circuit. We will consider the coarse delay first. To measure the delay, the starting point (zero range), must be established. This has been done in the synchronizer system. The A pulse from the synchronizer is used to trigger the coarse delay circuit in the range system.

Coarse Delay Circuit

The coarse delay is measured by a special type oscillator called the phantastron (fig. 13-16). Plate current in the oscillator tube is cut off before the A pulse arrives. The A pulse drives the tube into conduction so that the plate starts to draw current and the plate voltage drops. The output of the tube is a square wave pulse or gate. The leading edge (left-hand edge) occurs the instant the tube starts to conduct. It, therefore, is fixed in the radar's time system and represents zero in the radar's range system.

As in the blocking oscillator, the shape and duration of the phantastron's output gate is determined by the circuit components and is independent of the input trigger. (The complete phantastron circuit will be covered in a later course.) But in this case, one of the components in the circuit is variable. The wiper arm of the range potentiometer shown in the figure moves when the range handcrank is rotated. The voltage from the potentiometer changes the characteristics of the phantastron circuit which in turn varies the width of its output gate. Thus the trailing edge (right-hand edge) of the gate is movable and the width of the gate is proportional to range. The voltage from the potentiometer can vary the width of the gate to represent the entire ranging limits of the radar.

The phantastron circuit produces a very linear delay for ranging purposes. The time of occurrence of the trailing edge of the phantastron gate however, is not sufficiently accurate for fire control ranging. Therefore the length of the phantastron gate is considered to be the coarse range to the target.

Fine Delay Circuit

The fine delay circuit produces reference marks, 6.1 microseconds apart, similar to the ones in the synchronizer system, but the range reference marks are movable. The frequency of their occurrence is constant, but the movable marks can be shifted in time from the reference marks in the synchronizer.

The 163.88 KC oscillator in the synchronizer provides the reference voltage for the fine delay circuit of the range system. The reference voltage is divided into four sine wave voltages in a phase-splitting circuit. (A transformer will shift the phase of a voltage 180°, while an RC circuit can produce a 90° phase shift of a

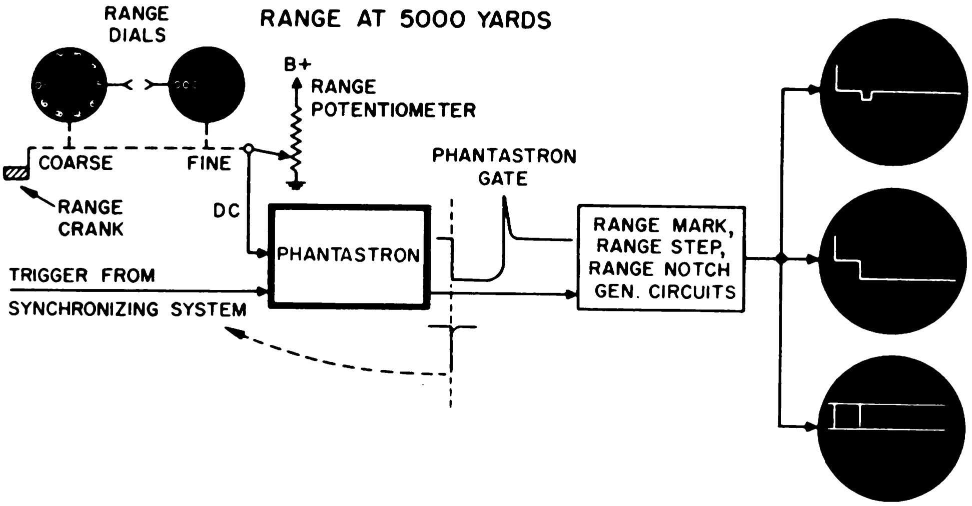

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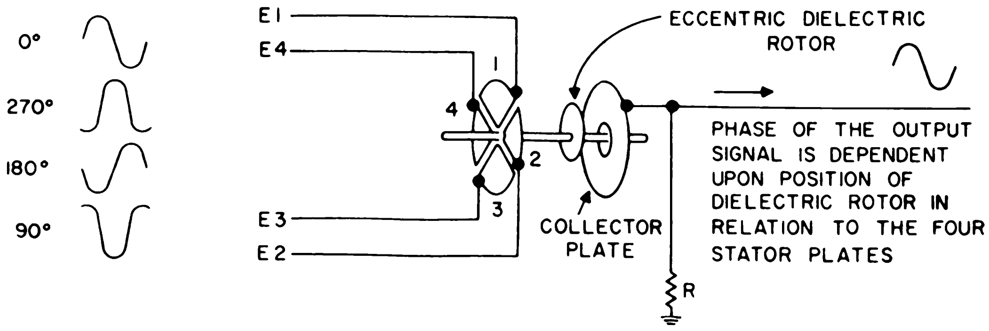
Figure 13-16.—Range coarse delay circuit.

voltage.) The output of the phase-splitting circuit is four sine wave voltages with a phase relationship of 0°, 90°, 180°, and 270°.

When you studied basic electricity you learned that there is a relationship between the electrical phase of a sine wave voltage and time. Since the positive peaks of the reference voltage are 6.1 microseconds apart, the positive peaks of the four sine-wave output voltages are separated from one another by about 1.5 microseconds or 250 yards of range. A range accuracy of 250 yards is not precise enough for fire control purposes. Thus the time delay as represented by the phase of the reference voltage must be further refined.

The four sine wave voltages are applied to a specially construcred capacitor, called a vari-phase capacitor. One of the plates of the capacitor is divided into four insulated segments (fig. 13-17). The voltages are applied one each to the segments of the plate. The dielectric rotor of the capacitor is slightly larger than one of the plate segments and is movable. The rotor is moved by range, one revolution is equal to 1,000 yards of range. The output of the vari-phase capacitor is a sine wave voltage whose frequency is 163.88 KC per second and whose phase can be varied from the reference voltage through 360°. The phase difference between the reference voltage and the output of the capacitor is equal to a time delay that is proportional to a range of zero yards to 1,000 yards. The amount of delay is dependent upon the range setting in the radar. The output sine wave voltage is distorted into spikes to produce the fine delay reference marks.

The time delay which is proportional to the range set in the radar is determined by correlating the fine delay with the coarse delay. The analogy of the minute and hour hands of a clock


0°
270°
180°
90°
E1
E4
E3
E2
1
2
3
4
ECCENTRIC DIELECTRIC ROTOR
COLLECTOR PLATE
PHASE OF THE OUTPUT SIGNAL IS DEPENDENT UPON POSITION OF DIELECTRIC ROTOR IN RELATION TO THE FOUR STATOR PLATES
R

12.317

Figure 13-17.—Vari-phase capacitor.

which we used in the synchronizer system would serve equally well here to describe the need for the correlation of the two delays.

In figure 13-18 you can see that the phantastron gate is the input to a blocking oscillator. The trailing edge of the gate which swings sharply positive triggers the blocking oscillator. The output of the blocking oscillator is an 8-microsecond gating pulse. The gating pulse is the input to the coincidence amplifier. Somewhere within this gate is the time delay proportional to range. The movable reference marks are the second input to the coincidence amplifier. When both inputs are present simultaneously, the amplifier will have an output. The fine delay plus the coarse delay has established the exact time delay for the range set in the radar. The output of the coincidence amplifier is amplified and then sent to the indicating system as the range pulse. In the indicating system the range pulse is used as a trigger to generate a range mark, range step, or range notch, depending on the type presentation of the radar scope, and a range gate for the tracking system.

In our discussion of the range system we referred to the time delay as representing range set in the radar and not as target's range. Radar ranging deals with the simultaneous occurrence of the movable range pulse and the target's video pip. When the two are coincident the radar's range is equal to target range. Since both the target's video pip and the range mark or notch are displayed in the indicators, it is a simple matter to move the range mark to make them coincident.

INDICATOR SYSTEM

Referring back to figure 13-4, we will now discuss the A-trigger in the indicator system. As was brought out in the discussion of the synchronizer system, the A-trigger is generated before the mod trigger. The time between the

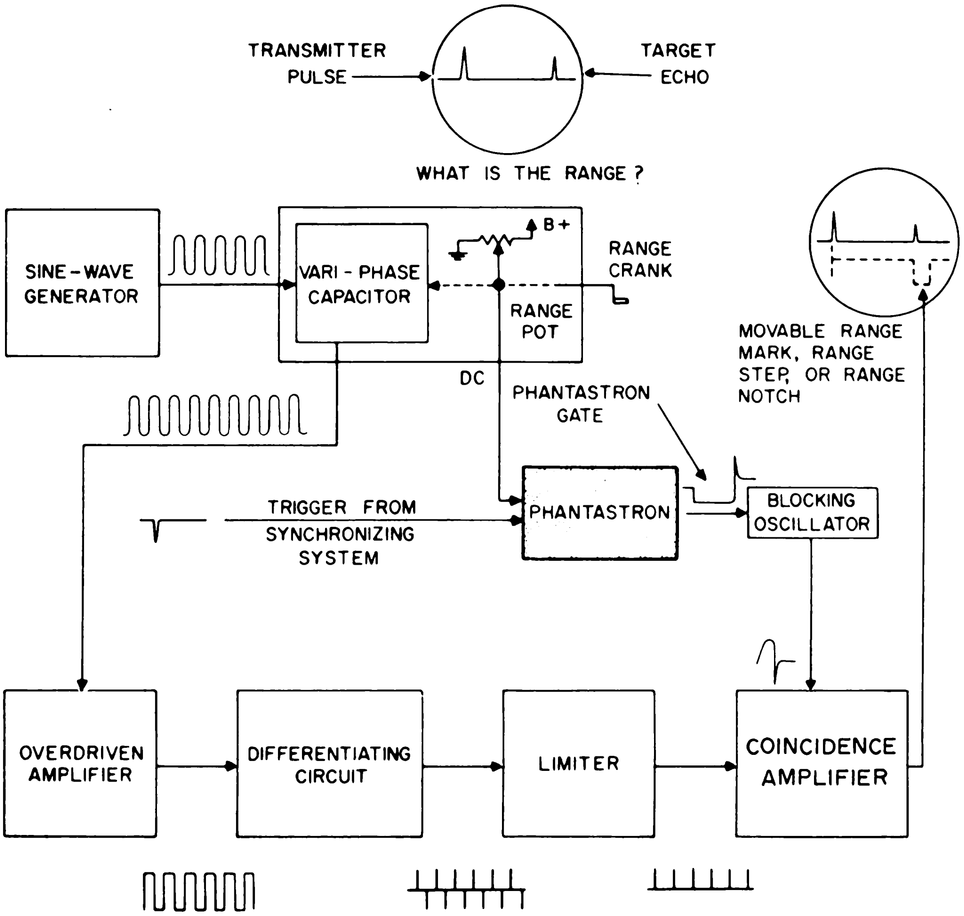


Figure 13-18.—Range delay circuit.

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two triggers is used in the indicator system to start the indicator scopes conducting and to allow the time necessary for the indicator sweep voltages to position the display so that it will start at the same spot on the scope for each transmitted pulse regardless of the radar's PRR.

The indicator scopes are normally blanked, that is cut off, except during the range sweep time. Therefore, when the range sweep voltage returns the indication to its start position the "fly back" of the range line is not seen. The persistency of the scope gives the impression of continuous conduction. The length of the range sweep determines the duration of the unblank voltage to the indicator scopes. Only the video received while the unblank voltage is present will be displayed.

Range Sweep

There are two range sweeps in the radar—MAIN-sweep and PRECISION-sweep. When the main- or A-sweep is used the indicators display the entire range limits of the radar. The main sweep voltage generator is triggered by the A-trigger from the synchronizer. When the precision or R-sweep is used the indicators show the section of the main sweep about the range of the target. Since the occurrence of the precision sweep is variable with target range, its sweep voltage generator is triggered by the movable range pulse from the range system.

Figure 13-19 shows a simplified block diagram of the main and precision range sweep channels. All the indicators have the same range sweep at the same time. Normally the main sweep is used to acquire a target. Once the target is acquired in the beam the sweep is shifted to precision. The expanded view of a small segment of range in precision sweep enables the operator to measure target's range more accurately.

Angular Sweep

The B-type and E-type indications show the range to a target plus its position with respect to the boresight axis of the antenna. The radar indicator's presentations were covered in chapter 12 of this course. The range line represents the forward going range sweep across the face of the scope. When the range line passes through the centerline axis of the scope, it is considered to be coincident with the boresight axis of the antenna. The target's angular position is displayed by moving the range line an amount proportional to the feedhorn offset from the antenna's boresight axis.

The two-phase reference generator, which we discussed under scanning in this chapter, provides a reference voltage whose phase indicates the direction of the feedhorn's offset from the nutation axis. The reference voltage from the generator is applied to a control transformer synchro whose output voltage indicates the amount of the feedhorn displacement. This voltage is the input to the angle sweep generator. In the sweep generator (fig. 13-20) the voltage is amplified and sent to the indicators where it is used to deflect the range line in the B- and E-scopes so that the line will follow the feedhorn in the train or elevation axis as it scans the area about the target. The phase of the voltage is shifted 90° for use in the E-scope. The range line is deflected an amount proportional to the position of the feedhorn regardless of the type of scan.

Video Signals

Video signals from the i-f amplifier in the receiver are sent to the video amplifier of the indicating system (fig. 13-2). The video amplifier has two channels, the A-video and the B-video channels. The input video signals are applied to both channels. The A-video is used in the A-type presentations. In this type presentation the video signal appears as a vertical deflection of the "A" sweep. The range notch signal from the range system is added to the A-video signal and both are sent to the A-type indicators.

The B-video is used in the B- and E-indicators. These scopes have intensity modulated displays and the video signals appear as a bright spot on the scope. The range mark signal from the range system is mixed with the B-video in the amplifier and the signals are sent to the indicators.

AUTOMATIC TRACKING SYSTEM

The tracking system keeps the radar "on target." The radar tracking system works in conjunction with the director power drives and the computer. The interconnections between these equipments was outlined in the beginning of this chapter. Therefore, we will only consider the radar's tracking system here.

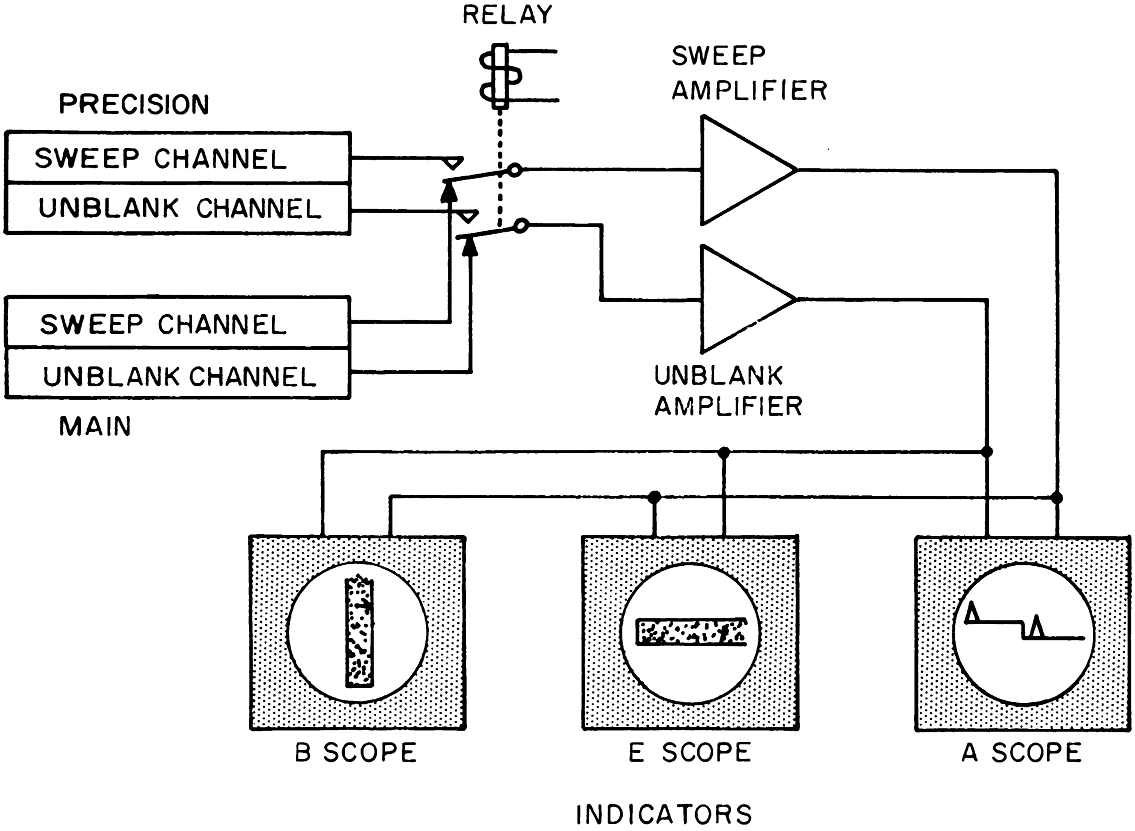

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Figure 13-19.—Main and precision channels.

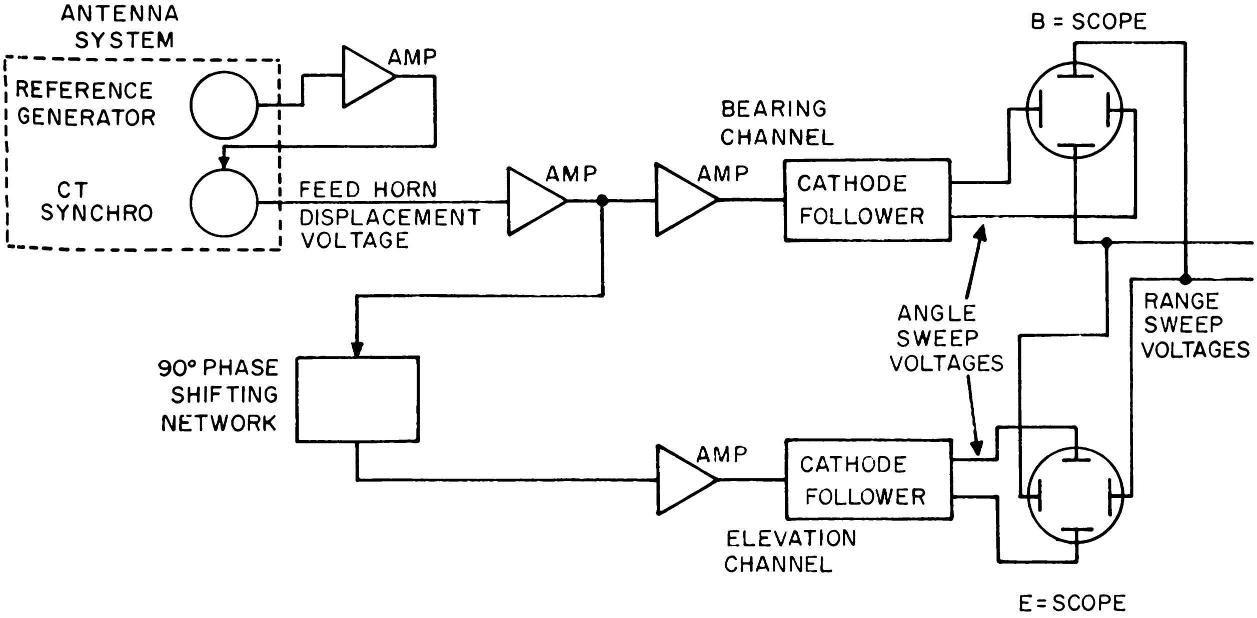

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Figure 13-20.—Angle sweep generator.

Range Tracking

It is the job of the range tracking system to drive range to keep the target's pip in the notch. From its job you can reason that the range tracking system is a servosystem. The first thing the tracking system must do is to determine if the pip is in the notch. If the pip is not in the notch, the tracking system must detect the error and drive the range system so that the pip and the notch occur simultaneously.

A circuit similar to a coincidence amplifier is used to determine if the target's pip is in the notch. A trigger pulse called the range gate is generated at the same time as the range notch. The range gate is one input to the amplifier. The second input is the video signal. If both signals are present in the amplifier there will be an output. An output signifies that the pip is in the notch.

Determining the amount and the direction of a range error is a more difficult job. This is the job of the range error detector. The sensitivity of the error detector is increased by using a balanced network. In one half the network undelayed, video signals are applied. If the range is correct this video signal will be coincident with one edge of the range gate. The video signal is also applied to a delay network. It takes the video signal a fraction of a microsecond to pass through the delay network. The delay is approximately equal to the duration of the range gate. The delayed video signal is applied to the other half of the balanced network. If range is correct the delayed video will occur at about the same time as the other edge of the range gate.

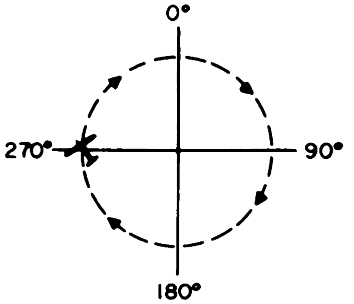
If range is correct an equal amount of the undelayed and the delayed video signals will be in the gate and the error detector will be in balance. If, however, the range drifts away from the correct value, more of one of the video signals will be in the gate and less of the other video signal. The error detector will be out of balance and will send an error signal to the range servosystem. The polarity of the error signal indicates the direction of the error. This is determined by which video signal is strongest in the gate. The amount of the range error is determined by comparing the strength of the video signals in the gate.

The video signals in the range gate are used to select the target for the tracking system. When the video signal and the range gate occur simultaneously an output from the range tracking system is used to start the automatic gain control in the receiver and to start automatic tracking in train and elvation of the gated signal.

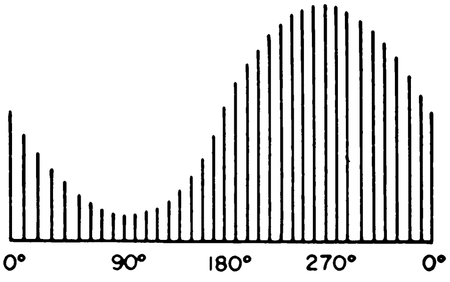
Train and Elevation Tracking

The radar's angle error detecting circuits provide correction signals to the director power drives. The correction signals are proportional to the target's displacement from the nutation axis of the antenna. Target displacement is detected by comparing the video signals from subsequent pulses. We will look at a series of video signals from a target to see how the error signal is detected. Assume the radar is in conical scan and locked-on the target. For this discussion we will place the target in the left-hand portion of the beam coverage of the radar (fig. 13-21); normally, in automatic tracking a target would not be this far off of beam center.

When the center of the beam (fig. 13-21), is at 0° the video return from the target will be relatively small. As the center of the beam



PATH OF BEAM DURING SCANNING



INCOMING ECHO PULSES FROM TARGET
DURING ONE SCAN CYCLE

12.321

Figure 13-21.—Amplitude modulation of the video signal.

rotates in a clockwise direction, each successive video signal will become smaller until at 90° we would receive a minimum video signal. As the beam center continues to move the amplitude of the video signals will increase until a maximum signal is received when the beam center is on target at 270°. Further clockwise rotation moves the beam center away from the target and the video will reduce in amplitude.

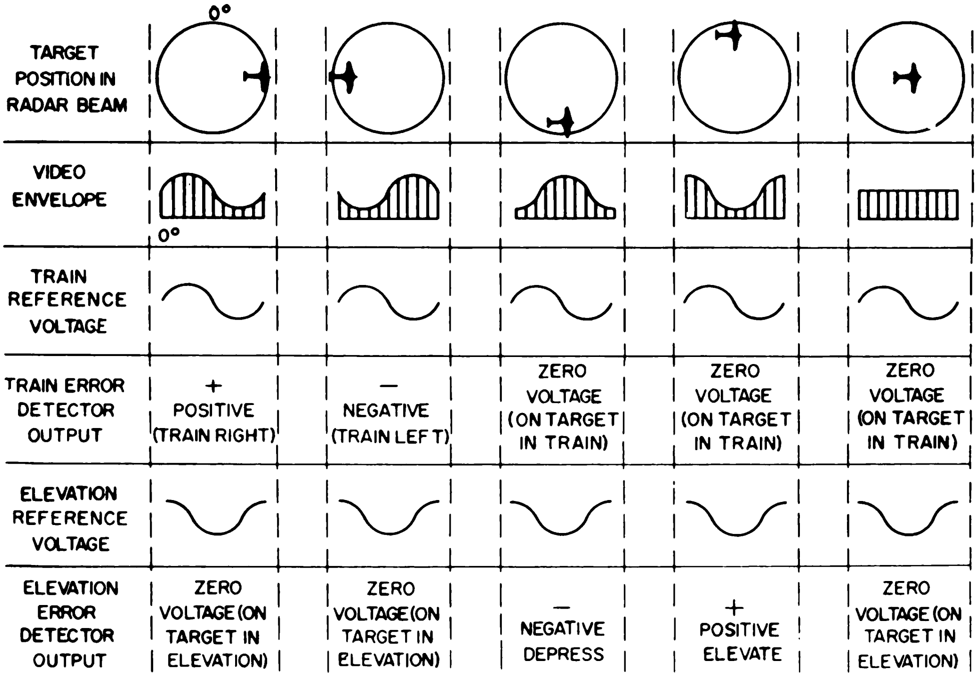
Notice in the figure that the video signals for a complete nutation of the feedhorn forms a sine wave. The sine wave is called the video envelope. The frequency of the video envelope is the same as the scan rate of the radar. The phase of the envelope is established by the position of the target relative to the center of the beam coverage of the radar. If the target had been to the right of the center of the coverage of the radar beam, the phase of the envelope in the figure would have been inverted. The amplitude modulation of the video signals established the amount of target displacement from the center of the beam coverage of the radar. If the target had been in the center of the beam coverage the video signals would all have the same amplitude.

The two-phase reference generator in the antenna established the position of the feedhorn relative to the nutation axis of the antenna. The generator provides the reference voltages for the train and elevation error detector circuits. The elevation reference voltage is 90° out of phase with the train reference voltage. The error detector circuits compare the phase of its reference voltage with the phase of the video envelope. The phase comparison (fig. 13-22), indicates the direction of the error. The amplitude modulation of the video envelope is compared to the amplitude of the reference voltage to determine the amount of error.

ANTIJAMMING CIRCUITS

The operational characteristics of a radar, such as its carrier frequency, transmitter power, pulse width, pulse repetition rate, and scanning rate are radiated into space and therefore can be detected by an enemy. An enemy can use this information to counter the use of our radar. For example, if the enemy knows the radar's carrier frequency, he can transmit an overpowering signal at that frequency and saturate the radar. If he uses a c-w transmission our radar scope would be jammed over the entire range of the radar. This is an electronic countermeasure (ECM), to our radar.

To counter the countermeasures the radar has many built-in ECCM circuits. The ECCM


0°
TARGET POSITION IN RADAR BEAM
VIDEO ENVELOPE
0°
TRAIN REFERENCE VOLTAGE
TRAIN ERROR DETECTOR OUTPUT
+ POSITIVE (TRAIN RIGHT)
— NEGATIVE (TRAIN LEFT)
ZERO VOLTAGE (ON TARGET IN TRAIN)
ZERO VOLTAGE (ON TARGET IN TRAIN)
ZERO VOLTAGE (ON TARGET IN TRAIN)
ELEVATION REFERENCE VOLTAGE
ELEVATION ERROR DETECTOR OUTPUT
ZERO VOLTAGE (ON TARGET IN ELEVATION)
ZERO VOLTAGE (ON TARGET IN ELEVATION)
— NEGATIVE DEPRESS
+ POSITIVE ELEVATE
ZERO VOLTAGE (ON TARGET IN ELEVATION)

12.322

Figure 13-22.—Phase comparison.

features are based on the known characteristics of a true target echo return and normal scope presentations. Normal echoes are approximately equal in duration to the width of the transmitted pulse. The strength of a normal echo is indirectly proportional to target range. Circuits in the radar receiver can attenuate or filter out echoes with an abnormal length or strength. These antijamming circuits are: the fast time constant (FTC), the instantaneous automatic gain control (IAGC), the sensitivity time control (STC).

The FTC circuit changes the RC time constant of one of the stages in the i-f amplifier. The time constant is changed so that signals with a longer duration than the transmitted pulse will be differentiated. The differentiated signal is attenuated. Signals of a normal duration are not affected by the FTC circuit. By use of the FTC circuit excessive sea return and low frequency modulated jamming are greatly reduced.

The IAGC circuit provides a negative feedback voltage to some of the stages in the i-f amplifier. The feedback voltage is proportional to the echo signal's duration and strength. The negative feedback is increased and the amplification is reduced for longer and larger signals.

The STC circuit makes the gain of the i-f amplifier a function of range. An RC circuit is placed in one of the stages of the amplifier so that the gain of the stage will increase exponentially with the output of the RC circuit. At short ranges the gain is minimum and as range increases the gain increases so that at maximum range the gain is maximum. The STC circuit is effective in detecting weak signals in excessive sea return and will compensate for the gain needed for weaker distant targets as contrasted with strong nearby targets.

The magnetron in fire control radars is tunable. Therefore when jamming is present at the carrier frequency, the magnetron's frequency can be shifted to avoid the jamming signal.

OPERATION CHECKS AND ADJUSTMENTS

Common Operating Adjustments and Control on Radars

As an FT 3, you must be familiar with the external adjustments on radars. Every radar has numerous controls and switches that are used in operating the set. You must learn what and where the controls are, and know what they will do. Radars must be operated under changing conditions. For example, the radar set may be used as a search radar if information from the search radars is unavailable. Most radars have displays and controls to acquire designated targets and to track targets once they are acquired. The FT must analyze a given situation and be able to adjust the controls so as to obtain the maximum information from the set, regardless of operating conditions. Controls that are frequently used while operating a radar include the gain control; range, bearing, and elevation handcranks; mode of operation switches, and antijam controls.

If the radar set is equipped with two or more types of cathode-ray display indicators, you should know which should be used, and under what conditions one is preferable to another.

Functions commonly controlled in a radar set may be grouped under three headings. The first group includes those controls that are adjusted and set before starting to operate the radar. These are daily adjustments that are made to ensure peak performance of the equipment. This group includes:

1. the controls or potentiometers that control the regulation of operating voltages and currents.
2. the calibration controls.
3. the tuning controls.

The second group of controls includes the voltage controls for the video indicators. In general, they are:

1. the focus control
2. the intensity control.
3. the vertical and horizontal centering controls.

The third group of controls includes those that are frequently used while operating the radar. This group includes:

1. the gain control.
2. the manual range, bearing, and elevation handcranks.
3. track and acquisition switches.
4. antijam switches and controls

Obviously, we have not listed all the various radar controls. Only the more typical ones are covered.

One of the best ways to become familiar with the controls on any piece of equipment is to actually operate the gear. We suggest that you use every opportunity to operate equipment

This practice will provide you with the knowledge of how the equipment works under all types of atmospheric conditions and in all modes of operation. Not only will you become more familiar with the various controls but you will see how the radar works when it operates at its peak performance. When you see a radar operating at its maximum efficiency, a visual performance standard is impressed upon your mind.

CHAPTER 14

CONTINUOUS-WAVE AND PULSE-DOPPLER RADARS

In this chapter we cover the characteristics of fire control continuous-wave radar and pulse-Doppler radar, and their principles of operation. We will discuss the continuous-wave radar first, since it is the simpler of the two types; then we will take up the pulse-Doppler radar. This chapter will complete our discussion of fire control radars. At the end of the chapter we briefly introduce the subject of telemetry. Telemetering equipment uses electromagnetic waves as a link to transmit data over great distances. Telemetry is a relatively new field to the FT rating, but your background in radar and servomechanisms will help you to understand its basic principles.

CONTINUOUS-WAVE RADAR

We will start with an elementary continuous-wave (c-w) radar with a minimum of essential components, (fig. 14-1). The transmitter continuously radiates r-f energy of a constant frequency. There is no timing circuit because the transmitter operates continuously. The purpose of the modulator in the transmitter is to shape the high-power input of the r-f oscillator. Because of the radar's continuous operation its peak power is equal to its average power, and its duty cycle is unity. Targets in the radar beam reflect some of the r-f energy back to the receiver antenna.

A separate receiver antenna is used because the receiver operates continuously and simultaneously with the transmitter. There is some danger that the transmitted energy will enter directly into the receiver antenna. In other words, there would be crosstalk between the transmitter and the receiver. The crosstalk can be reduced by locating the antennas some distance apart, and by making them highly directional. If a target is moving toward or away from the radar, the reflected signal is shifted in frequency. The shift in the frequency of the reflected energy is due to a characteristic of wave motion called the Doppler effect or Doppler shift. The difference between the transmitted frequency and the echo frequency is used to detect the target.

A weak sample of the transmitted r-f energy is sent to the receiver, where it is heterodyned in the mixer with the echo signal. The output of the mixer is due to the frequency difference between the input signals, caused by the Doppler shift in the echo. The output of the mixer is amplified, detected, and sent to the indicator system. Note that there is no i-f stage in the receiver. This greatly reduces its sensitivity. Since the radar operates continuously, it can theoretically detect targets down to almost zero range. But the radar has no time reference, and therefore cannot measure range. The change in the echo frequency due to the Doppler shift is proportional to the target's velocity in the range line and thus can be used to obtain target's range rate.

A stationary target will not produce a Doppler shift of the echo frequency, and the radar is "blind" to this target. The amplifier in the receiver is tuned to a narrow bandwidth containing the frequencies in the Doppler shift. The Doppler shift frequency band is measured in kicocycles, while a pulse radar's bandwidth is measured in megacycles. The narrow bandwidth will give the radar a high signal-to-noise ratio. Most of the noise and clutter, such as originates from sea return, land masses, and other unwanted targets, will be rejected by the amplifier. Moreover, we can tune the amplifier to a section of the Doppler shift bandwidth so that only the signals from targets with a given range rate will be passed through the amplifier. For example, we could tune the amplifier to accept only those frequencies which we would expect from an attacking aircraft's Doppler shift.

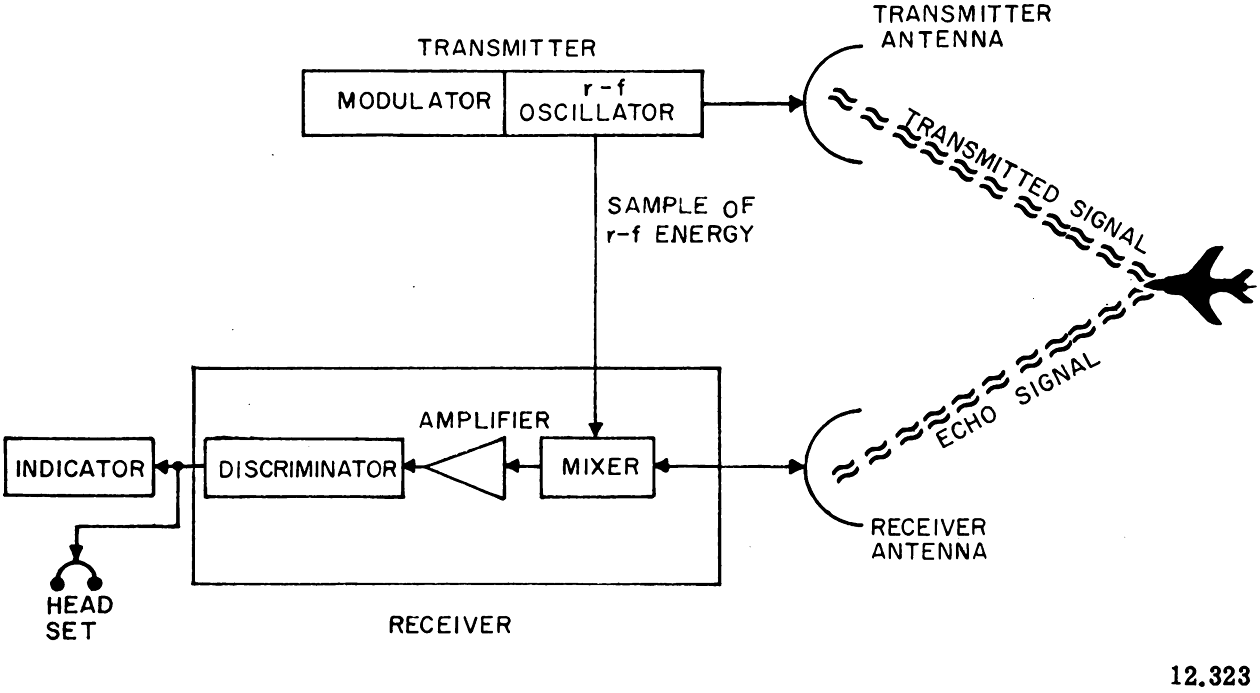


Figure 14-1.—Elementary c-w radar.

The radar would then single out this type of target from all others. This gives the radar a target selection capability which is a distinct advantage in some circumstances. Now let's discuss the Doppler effect, since it is the basis of a c-w radar's operation.

DOPPLER EFFECT

The Doppler effect, which bears the name of its discoverer, John C. Doppler, is applicable to all wave motion, (such as sound, radio, and light waves). The Doppler effect pertains to the change in frequency between the source of the wave motion (transmitter) and the observer of the wave motion (receiver) when the distance between the transmitter and the receiver is changing. That is, if either the transmitter or the receiver is moving toward or away from the other, the received frequency will not be the same as the transmitted frequency.

You can actually notice or sense the Doppler effect in some circumstances. For example, assume you are in a car which is passing a large truck. As you know, this can be a noisy affair, but we will be referring to the pitch of the noise, not the volume. The frequency of the sound waves determines the pitch of the sound. As the car approaches the truck, the relative motion between the source of the sound waves (the truck), and the receiver of the sound waves (you, in the car), is the resultant of the two motions, or your closure rate with the truck. As you approach the truck, its sound waves hit your ear at a certain frequency, (pitch). Because the car is closing with the truck you will not hear the same frequency that the truck is actually generating. The frequency and the pitch of the noise will be higher. The frequency that you hear as you pull ahead of the truck, increasing the distance between you and the truck, is lower than the actual noise frequency. You will hear the actual noise frequency only when the distance between you and the truck is not changing.

It is fairly easy to reason why the relative motion changed the received frequency by analyzing the situation. As the car approached the truck, the relative motion caused your ear to receive more cycles per second than when there was no relative motion between you and the source of the sound. On the other hand, as you moved away from the source of the sound the relative motion caused you to encounter fewer cycles per second than when there was no relative motion between you and the source.

Therefore, the higher the relative motion between the transmitter and the receiver the greater the frequency change. The direction of the relative motion determines the direction of the frequency change. When the relative motion is decreasing the distance, the received frequency is higher than the transmitted frequency; conversely, when the relative motion is increasing the distance, the received frequency is lower than the transmitted frequency.

The transmitted frequency and the speed of the transmitted waves in space affect the amount of the frequency shift. These two factors—the transmitted frequency and the speed of proprogation—establish the length of the transmitted wave. The wavelength and its velocity determine the number of cycles per second that the receiver will intercept. The wavelength is affected by the relative motion between the transmitter and the receiver.

We can now establish the relationship between the amount of a frequency shift and its determining factors; that is, the transmitted frequency, the velocity of the wave, and the relative motion between the transmitter and the receiver. Although a c-w radar deals with radio waves, we will continue to use sound waves for our explanation. The Doppler effect applies to both types of waves, but the figures for sound are smaller and easier to handle. We will consider a problem where the source of a sound (a whistle), is moving and the receiver is stationary. Assume the whistle is generating sound waves at a frequency of 200 cycles per second. At the end of one second there will be a series of 200 cycles in space. Sound waves travel approximately 1,100 feet per second in air. Thus the first wave would be 1,100 feet away from the whistle when the last wave in the series leaves the whistle. But assume the whistle is moving 100 ft/sec toward you, the stationary receiver. If this is the case, when the last wave in the series is emitted, the whistle would have moved 100 feet toward the first wave emitted. Hence the series of waves is contained in a length equal to 1,100 feet minus 100 feet or 1,000 feet, and the wavelength is equal to this distance divided by the frequency, or $[(1,100 - 100) \div 200)]$. The frequency you would hear is determined by dividing the velocity of the waves by their wavelength; in this example,

$$1,100 \div \frac{1,100-100}{200} = 1,100 \times \frac{200}{1,100-100} = 200$$

cycles per second. The Doppler effect has shifted the frequency by 20 cycles per second. If the whistle had been moving away from you, its motion would have been added to the wave's motion in the formula, resulting in a decrease in the frequency you would hear. Also note that if there was no motion there would be no Doppler shift. Therefore, if the generated sound's frequency and velocity are constant, the Doppler shift can be used as an indication of the relative motion (range rate) between a transmitter and a receiver.

If in the same example we assume the source of the sound to be stationary and the receiver to be moving, we could determine the Doppler shift by a similar formula. The velocity with which the sound waves are intercepted is equal to the velocity of the sound plus or minus the velocity of the receiver with respect to the transmitter. We could determine the sound's wavelength by dividing its velocity by its frequency. If we divide the velocity at which the waves are intercepted by their wavelength, we would have the received frequency of the sound. A comparison of the frequency generated by the transmitter and the received frequency will give us the Doppler shift. It is interesting to note that the amount of the Doppler shift is slightly greater when the transmitter is moving than it is when only the receiver is moving.

A continuous-wave radar operates by means of the same effect, except that electromagnetic waves are employed instead of sound. The transmitting antenna of the radar set beams uninterrupted energy of a constant frequency toward the target. The target reflects the energy, and becomes in effect a second emitter of waves. If target motion is in the line of sight with respect to the radar, the frequency of the returning echoes differs from that of the outgoing signals. The echoes are picked up by the antenna and are heterodyned in the receiver with a small reference voltage at the frequency of the outgoing waves. The difference value, or beat frequency, which results from mixing the reference and echo voltages, is the Doppler signal. The presence of this signal indicates a moving target, and the Doppler value in cycles per second serves as a measure of the relative speed (range rate).

Both the radar set and the target are transmitters and receivers of r-f energy. Ships motion in the line of sight will cause a change in frequency when the radar is transmitting and when it is receiving. Likewise, target motion will cause a Doppler shift when the r-f energy hits it and again when it reflects the energy. The total effect of the range rate in the two-way travel of the electromagnetic waves is therefore double the effect of the relative motion.

In textbooks that deal with the Doppler effect, it is shown that in two-way travel of electromagnetic waves, as in the c-w radar system, the amount of frequency change in cycles (f_d) is related to the relative speed in the line of sight (V_c) by a simple equation,

$$f_d = \frac{2V_c}{\frac{c}{f}}$$

in which f is the frequency of the reference signal, and c is the velocity of the radar waves. Since $\frac{c}{f}$ is the wavelength (λ) of the reference emission, the equation can be expressed in the following form:

$$f_d = \frac{89.4V_c}{\lambda}$$

where f_d is in cycles per second, V_c is in miles per hour and the wavelength, λ, is measured in centimeters. (The constant required to convert miles per hour to centimeters per second is 44.7; 2 x 44.7 = 89.4).

If the c-w radar emits radiation with a wavelength of 10 centimeters, then according to the equation the Doppler signal will vary by almost 9 cycles per second for each mile per hour of range rate. If the radiation has a wavelength of 3 centimeters, a typical value in microwave systems, then the Doppler shift amounts to almost 30 cycles per second for each mile per hour of range rate. For example, assume that the range rate for a certain air target is 600 miles per hour and the c-w radar system employs 3-centimeter radiation. When these figures are substituted in the equation, the resulting Doppler frequency is 17,880 cps. This would mean that the returning echo from the target would be either 17,880 cps higher or lower than the transmitted frequency. Let's take a basic c-w radar and see how this information is obtained and used.

BASIC C-W RADAR SET

In the elementary c-w radar (fig. 14-1) the Doppler frequency is extracted by beating the transmitted radio frequency directly with the echo frequency. This radar cannot determine if the Doppler shift is above or below the transmitted frequency. Therefore, the radar can only indicate a target's presence and its relative speed. If you were ever speeding while driving a car through a radar trap you have definite (and probably expensive) proof of the c-w radar's speed measuring ability. In figure 14-2 we have added a local oscillator so that the radar can determine the direction of the Doppler shift. The i-f and video amplifiers are not shown in the diagram.

The receiver contains a local oscillator whose output frequency L_o is beat in the first mixer with the sample of r-f energy f_o. The beat frequency ($f_o + L_o$) is fed to a second mixer. In this mixer the echo return ($f_o \pm f_d$), transmitted frequency ± Doppler shift, and $f_o \pm Lo$ are beat together. The output of the mixer is $L_o \pm f_d$ This frequency is amplified and fed to a discriminator. The discriminator is a frequency error-detecting circuit which is resonant at the L_o frequency. The purpose of the discriminator is to develop a d-c voltage output with a polarity that is determined by the direction of frequency shift from the L_o frequency and that has an amplitude that is determined by the amount of frequency variation from L_o. The output voltage may be zero, some positive voltage, or some negative voltage. No output is an indication of no Doppler. A positive voltage output is an indication of a Doppler shift in one direction. A negative voltage output is an indication of a Doppler shift in the other direction. The error voltage from the discriminator is applied to an indicating device such as a CRT scope.

In the receiver, the mixers phase-compare their input frequencies. The reference frequencies (f_o and L_o) must be COHERENT. That is, the phase relationship between the two frequencies must be constant with time.

For audio indication of the target the r-f sample is fed into a third mixer where it is beat with echo frequency $f_o \pm f_d$. The output of this mixer is the Doppler frequency. If the Doppler frequency is in the audio range, (approximately 15 to 20,000 cps) an audio device (headset) can be used to indicate the presence of a target.

For an experienced operator, the audio Doppler note of the target contains valuable information. For example:

1. Prop Modulation—Indicates a propeller-drive aircraft, and if it is multi-engine.
2 Turbine whine—Indicates a jet-powered aircraft, and if it is multi-engine.

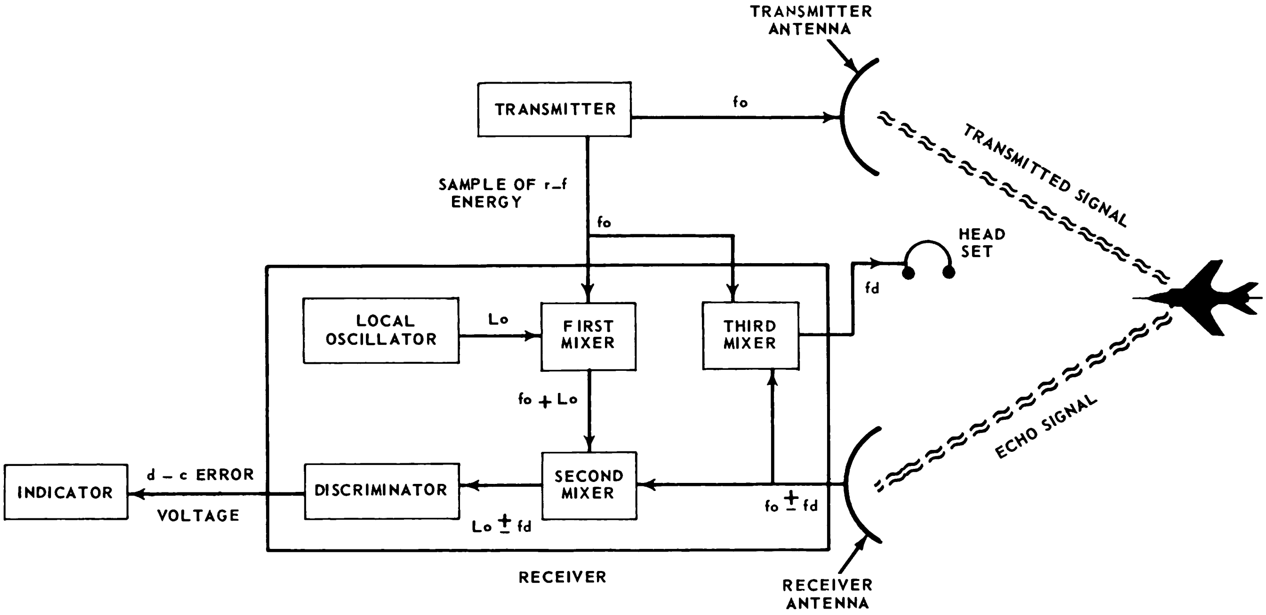


Figure 14-2.—Elementary c-w radar set.

3. Instantaneous changes in target course and speed.

The information in the audio Doppler is contained in the intensity and pitch of the audio note. The ability of an operator to distinguish these characteristics can be developed by training and practice. The information contained in the audio Doppler of the target will greatly aid in a tactical evaluation of the target.

Range Determination

It was mentioned earlier that a c-w radar can be modified to measure range. As you know, a radar uses the constant velocity of the r-f energy versus the passage of time to measure range. As it stands now, the c-w radar has no reference point from which time can be measured. If the r-f carrier is varied linearly with time, we could use the variation to determine the range to the target. There are three fundamental ways of altering or modulating the carrier: by varying the amplitude (amplitude modulation) the frequency (frequency modulation), or the phase (phase modulation). We will use a frequency-modulated c-w radar to see how range can be measured.

Frequency modulation (FM), involves a change of the radar's carrier frequency. In figure 14-2 the transmitter has two sections, the modulator and the r-f oscillator. The modulator is used to shape the signal to the r-f oscillator but it can also introduce an FM signal voltage. The FM voltage will cause the output of the r-f oscillator to sweep across a frequency band in an upward direction and then in a downward direction. The amount of time it takes to sweep across the band is a function of the radar's maximum range.

The frequency of the carrier is varied continuously and linearly with time. Therefore, the frequency being radiated when an echo is received will be different from the frequency of the echo. This difference results because the original frequency (frequency in the echo), traveled to the target and returned; during this time the transmitter varied its frequency. The frequency difference depends on the distance traveled and therefore can be used as a measure of range.

Modulation of the radar's carrier frequency in any one of the three fundamental ways can also be used to transmit intelligence, or for identification purposes. In a missile system where the radar receiver is remotely located (it is in the missile), and could receive from more than one transmitter, a preselected code is set up in the transmitter and in the receiver.

The code consists of one of the types of modulation superimposed on the transmitter's carrier frequency. The radar's receiver will only accept a signal with the proper carrier frequency and code. Once the identification has been established the code can be used to start a function or an action in the receiver, and thus the missile. The action could be the result of the missile arriving at some predetermined condition or position.

We have located the radar receiver in the missile. The receiver, therefore, is moving with the missile away from the transmitter. Let's look at this arrangement and see how it affects our basic c-w radar (fig. 14-2). The only direct connection between the transmitter and the receiver is the sample of the transmitted r-f energy. Obviously, with the receiver in the missile, a mechanical connection between it and the transmitter, which is located aboard ship, can not be used. Instead, an electromagnetic link is used to furnish the r-f sample. The c-w transmitter radiates two beams, a wide-angle reference beam and a narrow-illumination beam. Both beams contain all the modulations needed for coding.

The missile has a highly directional reference antenna system to receive the r-f energy in the wide-angle beam directly from the transmitter. A separate antenna system, also highly directional, is located in the forward section of the missile to receive the echo signal reflected from the target. The receiver operates in the same manner as previously described except that its outputs, instead of going to the indicator, are used in the guidance system of the missile. The forward antenna is positioned so that it is always pointing at the target and receiving the maximum amount of the reflected r-f energy.

ELEMENTARY C-W AND PULSE RADAR COMPARED

Let's look at a pulse radar in its simplest form. The transmitter generates a very short pulse of high energy radiofrequency. As the transmitter pulse leaves the antenna, the radar's receiver becomes operative, allowing it to receive and amplify any r-f energy reflected by a target. The time between the transmission of the r-f energy and the echo return is measured electronically and displayed graphically by a CRT. (cathode-ray tube).

Thus the pulse radar can measure range accurately, and does not depend on target's movement for detection. Therefore it can detect both stationary and moving targets.

The c-w echo is changed in frequency by a moving target. This change, as you remember, is called Doppler shift. The Doppler frequency is used for target detection, and to indicate the target's range rate. It is possible, by use of filter circuits, to reject all targets except those traveling at or near a selected velocity. Normally a c-w radar will not detect stationary targets. If the c-w radar radiates energy continuously, at a constant frequency, there is no reference by which we can measure range directly. Even with a form of carrier modulation its ranging is crude.

On the other hand, pulsed radar radiates energy at a selected time interval. This interval determines the usable range of the radar, Pulse radar, with its precise measurement of transit time, has a very accurate range measurement capability.

The pulse-Doppler radar combines the best features of c-w and pulse radar. The pulse-Doppler method uses high frequency c-w, in the form of short bursts, or pulses. The pulse repetition rate (PRR) is much higher than that of a conventional pulse radar, and the pulse length is longer.

A measure of the target's velocity toward or away from the radar can be obtained by means of the Doppler shift. This can be accomplished in the same manner as in c-w radar. We will use a simplified block diagram to show how the pulse-Doppler principle is applied to an elementary radar.

The master oscillator, shown in figure 14-3, provides the basic c-w energy. The output frequency (f_o) must be coherent. A pulse generator is used to chop the c-w energy into pulses for transmission. A target echo contains the transmitted frequency (f_o) and a Doppler frequency component (f_d). To extract the f_d frequency, we feed the output of the receiver and a small sample of the original f_o from the master oscillator into a mixer.

In the mixer the two signals set up a beat frequency. This is similar to the c-w radar, except that now the output of the mixer is pulsed at the PRR. When there is no returned echo (no target in the radar beam) the beat frequency is equal to that of the sample of f_o, and is decoupled from the phase detector.

A stationary target's echo has the same frequency as the sample of f_o. Under this condition the magnitude and polarity of the phase

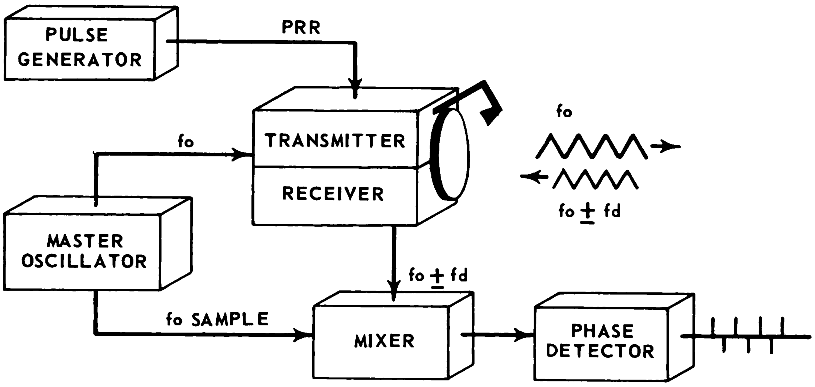


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Figure 14-3.—Elementary pulse-Doppler radar set.

detector output will be constant. A stationary target will appear as a fixed signal, which may be either positive or negative, on a A-scope. However, a signal of constant magnitude and polarity can be rejected by the automatic track circuits. From this it can be seen that the pulse-Doppler technique makes it possible to track targets through unrelated noise and clutter that would mask the targets in conventional pulse radar.

For a moving target, the mixer's output varies in magnitude and phase as f_o and $f_o \pm f_d$ go in and out of phase. Each output pulse is an envelope of sine waves whose amplitude will vary at the frequency of the Doppler (beat frequency) signal. These sine waves are the input to the phase detector, whose output is a series of pulses spaced at the PRR. The pulses vary in amplitude and, since they can be either positive or negative, are termed "bipolar." The indication of a moving target on an A-scope has a butterfly-like appearance.

Some pulse-Doppler radar systems do not use the Doppler frequency to obtain a measurement of target's range rate. In these radars the range rate is obtained by measuring the time rate of change of the range gate. This is similar to conventional pulse radars. The Doppler principle is used as a means to operate the radar's receiver with a narrow bandwidth and to reject unwanted targets and noise.

When the target reaches a velocity such that the Doppler frequency is greater than one-half the PRR, the true Doppler frequency can no longer be reproduced, as the sampling rate (PRR) is too low. To avoid this difficulty, the radar must shift to a higher PRR.

We mentioned earlier that the pulse-Doppler radar used a high PRR. This introduces a problem called "blind range." A blind range will occur if a target echo returns to the antenna at the same time another pulse is being transmitted. Since the receiver is closed by the duplexer, the return echo is not permitted to enter the receiver. In other words, the radar does not "see" the target. The radar is therefore blind at this range. At each PRR there are a number of time intervals at which blind range occurs. These intervals, and hence the blind ranges, vary with the PRR. In the radar, blind range is avoided by circuitry which automatically changes the PRR. During the acquisition phase the PRR is periodically changed.

In our c-w radar we could not measure range because we had no time reference. Pulse-Doppler radar can measure range by using transit time, as in the conventional pulsed radar. However, due to the high PRR, the transmitter will put out several pulses during the time required for a pulse to reach the target and return. To measure range, we must be able to distinguish between these pulses. Each pulse will strike the target and cause a video indication. Therefore it would be possible to use the transmitted time of one pulse as the zero time reference and obtain a false range using the echo of another pulse. To obtain the correct range we must ensure that the zero time reference and the echo return are from the same pulse.

Since the transmitted pulses occur at equally spaced time intervals and the range between pulses is identical, to obtain the correct range the radar range must be set in the correct pulse interval. Range from the designation system can do this. Once set, the radar can gate and track the target at the correct range.

The correct pulse interval can also be determined by the use of different PRRs. Only in the correct pulse interval will the relationship between the rangemark and target video remain constant when the PRR is changed.

The conical scanning method we discussed in the pulse radar chapter is sometimes called sequential lobing, because target information is gathered from a series or sequences of pulses. Another scanning technique, called monopulse or simultaneous lobing can obtain information on target range, bearing, and elevation from a single pulse.

MONOPULSE SCANNING

For target tracking, the radar discussed here produces a narrow circular beam of pulsed r-f energy at a high pulse repetition rate. Each pulse is divided into four signals which are equal in amplitude and phase. The four signals are radiated at the same time from each of four feed horns grouped in a cluster as shown in figure 14-4. The radiated energy is focused into a beam by a microwave lens. Energy reflected from targets is refocused by the lens into the feedhorns. The amount of the total energy received by each horn will vary depending on the position of the target relative to the beam axis. This is illustrated in figure 14-5 for four targets at different positions with respect to the beam axis. Be sure to notice, and remember, that a phase inversion takes place at the microwave lens similar to the image inversion in an optical system.

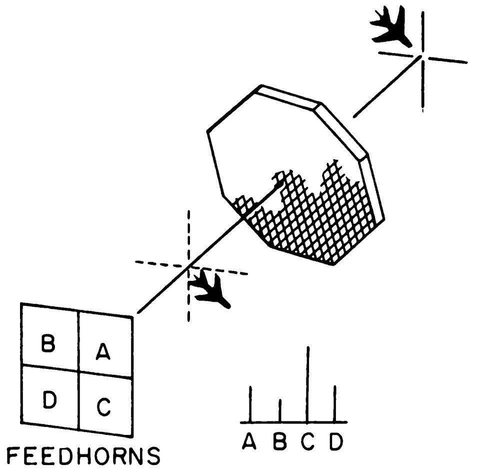

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Figure 14-4.—Monopulse technique.

The amplitude of returned signals received by each horn is continuously compared with those received in the other horns, and error signals are generated which indicate the relative position of the target with respect to the axis of the beam. Angle servocircuits receive these error signals and correct the position of the radar beam to keep the beam axis on target.

The traverse (train) signal is made up of signals from horns A and C added and from horns B and D added. By waveguide design the sum of B and D is made 180° out of phase with the sum A and C. These two are combined and the traverse signal is the difference of (A + C) - (B + D). Since the horns are positioned as shown in figure 14-5 the relative amplitudes of the horn signals give an indication of the magnitude of the traverse error. The elevation signal consists of the signals from horns C and D added 180° out of phase with A and B, i.e., (A + B) - (C + D). The sum or range signal is composed of signals from all four feedhorns added together in phase. The range signal is also used as a phase reference for the traverse and elevation error signals.

The traverse and elevation error signals are compared in the radar receiver with the range or reference signal. The output of the receiver may be positive or negative pulses, the amplitude of which is proportional to the angle between the boresight (beam) axis and a line drawn to the target. The polarity of the output pulses indicates whether the target is above or below, to the right or to the left of the boresight axis. Of course, if the target is directly on the boresight line, the output of the receiver is zero, and no angle tracking error is produced.

TELEMETERING

Guided missiles and their control systems are given a series of comprehensive operational tests aboard ship. The results of these tests, however, may be very different when the missile is actually in flight. Temperatures, pressures, and accelerations encountered in flight may significantly change the operation of the missile. Electronic components and other types of equipment may react very differently under the stress

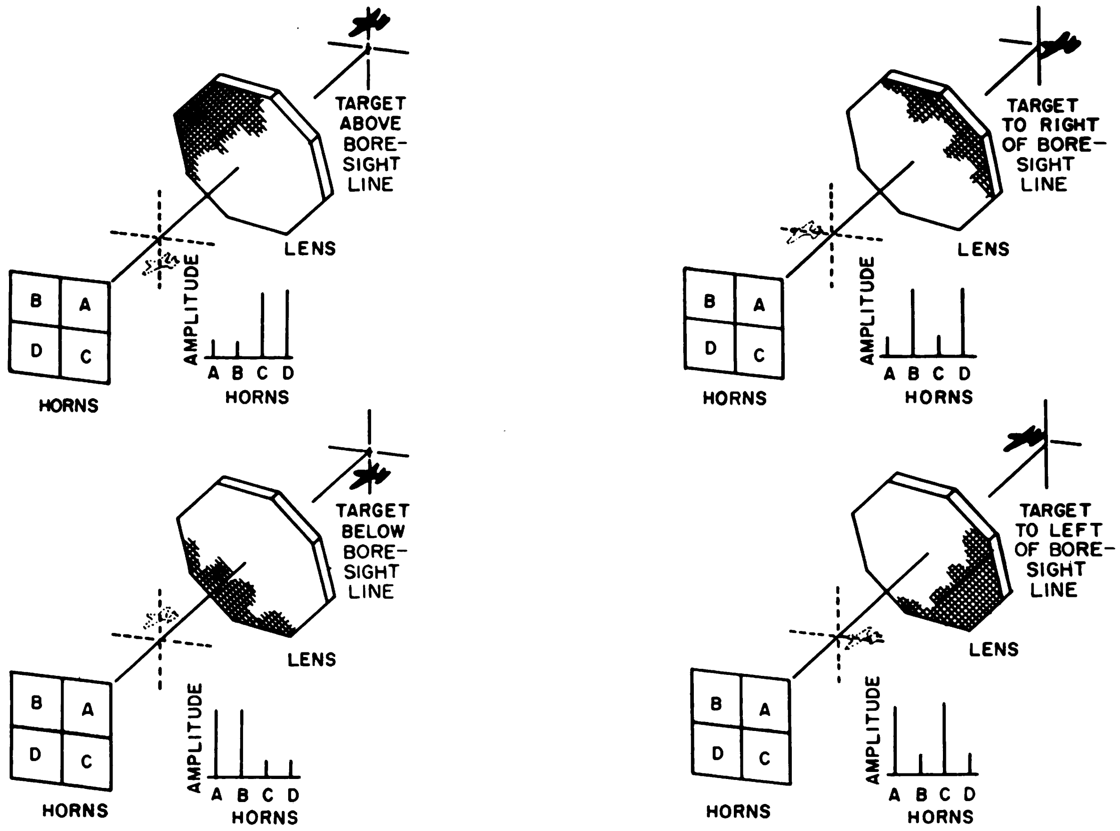

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Figure 14-5.—Amplitude changes of received energy with target position.

of flight conditions. If a missile component or function is faulty in flight, you will soon become aware of an unsuccessful firing, but the reason for the failure will remain unknown. For these reasons telemetering systems have been developed to monitor the operation of various functions of the missile in flight.

The word "telemeter" is of Greek origin and means "measurement from a distance". Telemetering of data related to the missile's internal operation is accomplished by a radio link. Missile telemetering systems carry out the following major processes:

1. Observation of missile functions, including the miss distance.
2. Conversion of the measured quantity into electrical signals.
3. Transmission of the signals from the missile to the receiving station.

The receiving station:

1. Receives the transmitted signal.
2. Decodes the signal.
3. Displays selected data in visual form.
4. Records the data permanently for future use.

A simple telemetering system might measure only "yes-no" information such as whether or not the fuze is armed. This type of system tells when and if an event has taken place. A usual method is to change an audio modulation frequency each time an event takes place. The carrier frequency of the telemeter's radio link is continuously being modulated by a constant audio frequency, but when the event takes place the amount of the modulating audio frequency is changed. The modulation change gives evidence that the transmitter was working both before and after each successive event.

Many of the operational functions of the missile have a quantitative value that should be recorded in order to obtain a complete picture of the missile's operation. The missile's control surfaces are an example of this type of data. We would want to know when the control (the tail fin in figure 14-6), was deflected, in which direction it was deflected, and the amount of deflection.

The tail fin is mechanically connected to the potentiometer's wiper arm. When the tail fin is in its neutral position, A, the wiper arm is at its neutral position and the output signal to the subcarrier oscillator is zero volts. Movement of the tail fin will move the wiper arm off its zero position. The direction of the movement will determine the polarity of the output voltage, while the amount of the movement will determine the magnitude of the signal voltage.

The voltage from the potentiometer is used to control the frequency of the subcarrier oscillator (SCO). The output frequency of the SCO is changed by the input voltage so that the output frequency is a function of the angular position of the tail fin. A positive input voltage to the SCO may produce a decrease in the SCO's output frequency, and a negative input voltage may produce an increase in frequency.

END INSTRUMENTS

The sensing devices which are carried in the missile to monitor its operation are called end instruments. End instruments fall into two broad classes: PICKOFFS and TRANSDUCERS. In telemetering, the term "pickoff" is usually reserved for devices which collect data in electrical form and relay that data in electrical form. The term "transducer" generally is reserved for the devices that convert nonelectrical indications—for example, mechanical motion—to an electrical form which can be used for telemetry.

The end instrument must be aligned with the device it is measuring, and must neither impair nor exert undue influence on the quantity it is measuring. The entire telemetering system must be synchronized as to the time of occurrence of events in the missile's flight. For example, the recording system must be able to time such events as the intent-to-launch signal, launch time, end of boost, capture time, start of the beam riding, homing, or terminal phases, and any other event which may be important in the evaluation of the missile's flight.

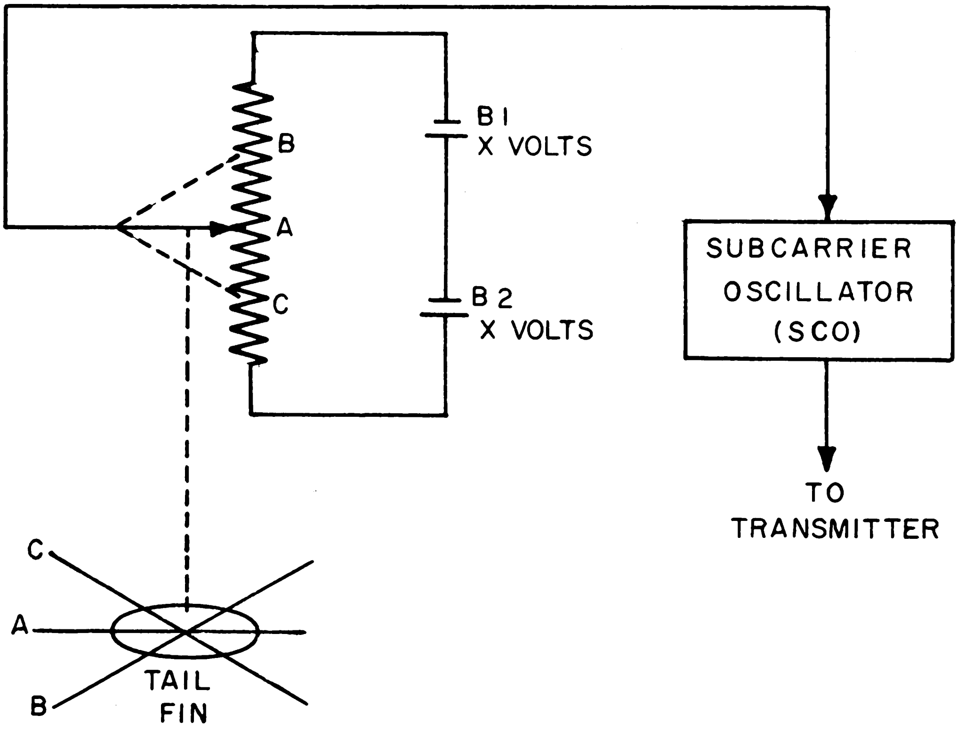

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Figure 14-6.—Subcarrier signal generator.

MULTIPLEXING

The missile telemetering system must transmit a large amount of data in a short period of time. The time available is the duration of the missile's flight. The missile is normally not recovered, and therefore is a one-shot device. Some form of multiplexing is used to provide the necessary number of data channels. Multiplexing is using the same circuit to transmit several messages simultaneously. There are two methods of multiplexing in general use: FREQUENCY DIVISION and TIME DIVISION.

In frequency division two or more signals are transmitted over a common path, with a common carrier wave, by using a different frequency for each signal. The signal frequencies are used to modulate the carrier wave for transmission. Each signal has an assigned frequency band.

In time division two or more signals are transmitted over a common path by using different time intervals for different signals. This type of multiplexing is a time-sharing system; items of information are transmitted one at a time in a regular sequence.

TELEMETERING TRANSMISSION SYSTEM

Now let's go back to our example of the tail fin channel. The output of the SCO goes to a telemetering transmitter. The transmitter receives input signals from several SCO's (usually 10 or 11). Each SCO monitors a separate function and has a different center frequency, such that its signal can be separated from the other SCOs. This system uses frequency division multiplexing and is called an f-m/f-m system.

The SCO outputs are summed at the input of the transmitter (fig. 14-7). The bandpass filters are used to prevent interference. The composite SCO signal, which contains all the individual signals, is used to frequency-modulate a low frequency oscillator. The output of the oscillator is channeled through a frequency multiplier, to increase the frequency to the carrier band, and through a power amplifier. The telemetric data is now ready for transmission to the receiving station.

The missile's telemetering exercise head contains the transmitters which generate and transmit the telemetric signals. The telemetering techniques and equipment for the most part are now standard in the Navy's RIM missiles. But there is a difference in the telemetering installations between missile types. Some missiles may have only one transmission system while others may require more than one. Naturally this depends on the amount of data needed to evaluate the missile's flight.

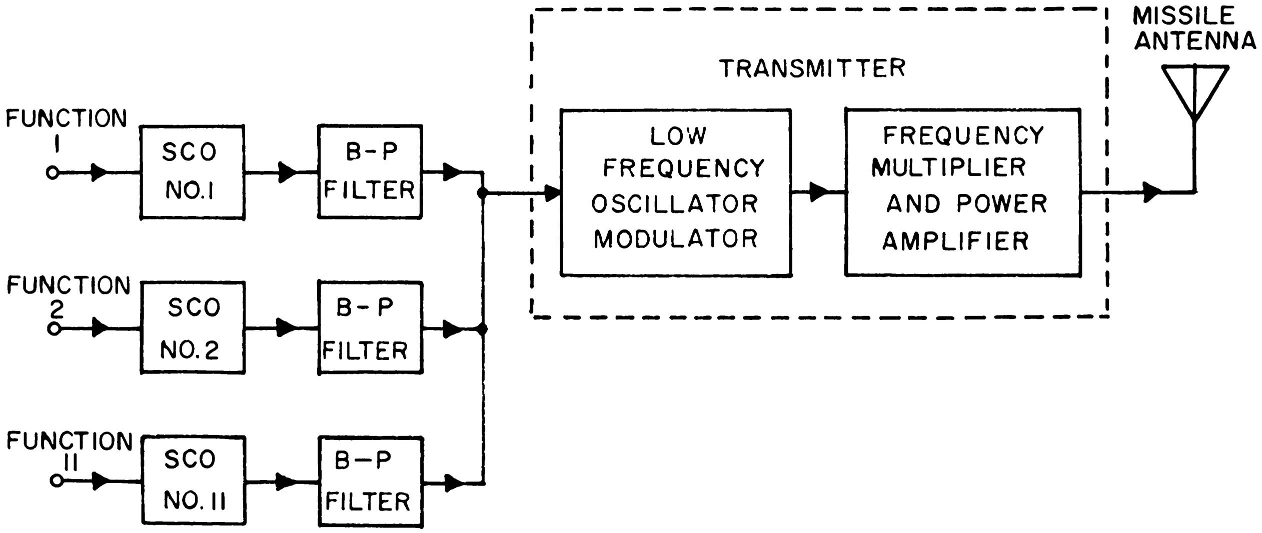

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Figure 14-7.—Telemetering transmitter, simplified block diagram.

RECEIVING STATION

The receiving station, aboard ship, receives the r-f carrier containing the missile information. The receiver demodulates the r-f signal to reproduce the composite subcarrier signal. The composite subcarrier is an envelope made up of the individual signals from the SCOs in the missile. The frequency-modulated subcarrier signal is recorded on a tape recorder as a permanent record of the flight. The individual signals contained in the subcarrier are extracted and recorded by an oscillograph to provide a graphic record for evaluation.

There are three separate receivers in the telemetering system. Missile flights which use only one r-f transmission are normally monitored by two of the receivers, one acting as a backup in case of a failure. Missile flights which have multiple r-f transmissions may use all three receivers. The tape recorder has four tracks, one for each of the receivers. The fourth track records timing signals, voice comments, event marks, the miss distance signal, and synchronizer (sync) signals. There are eleven channels in the oscillograph recording system. Thus all the signals in a subcarrier can be recorded simultaneously. If there is more than one subcarrier the tape can be played back and the information on the other subcarrier can be recorded by the oscillograph system.

The receiving system can be divided into three basic subsystems: the receiving and recording system, the miss-distance and recording system, and the timing and synchronization system. Figure 14-8 shows a simplified block diagram of the receiving and recording subsystem. There are two more receivers in the system, but except for their frequency band-pass their operation is similar to the one shown.

The receiver's r-f amplifier is a standard tuned amplifier centered about the carrier frequency. The amplified r-f signal is applied to a mixer, where it is beat with the output of the local oscillator to produce an i-f signal. This signal is amplified and sent to the discriminator, where the subcarrier signal is extracted from the i-f signal. The reproduced subcarrier signal is amplified in the output amplifier. This signal contains all the frequency components which represent the measured information in the missile.

The reproduced composite subcarrier signal is the input to the recording system, in which it

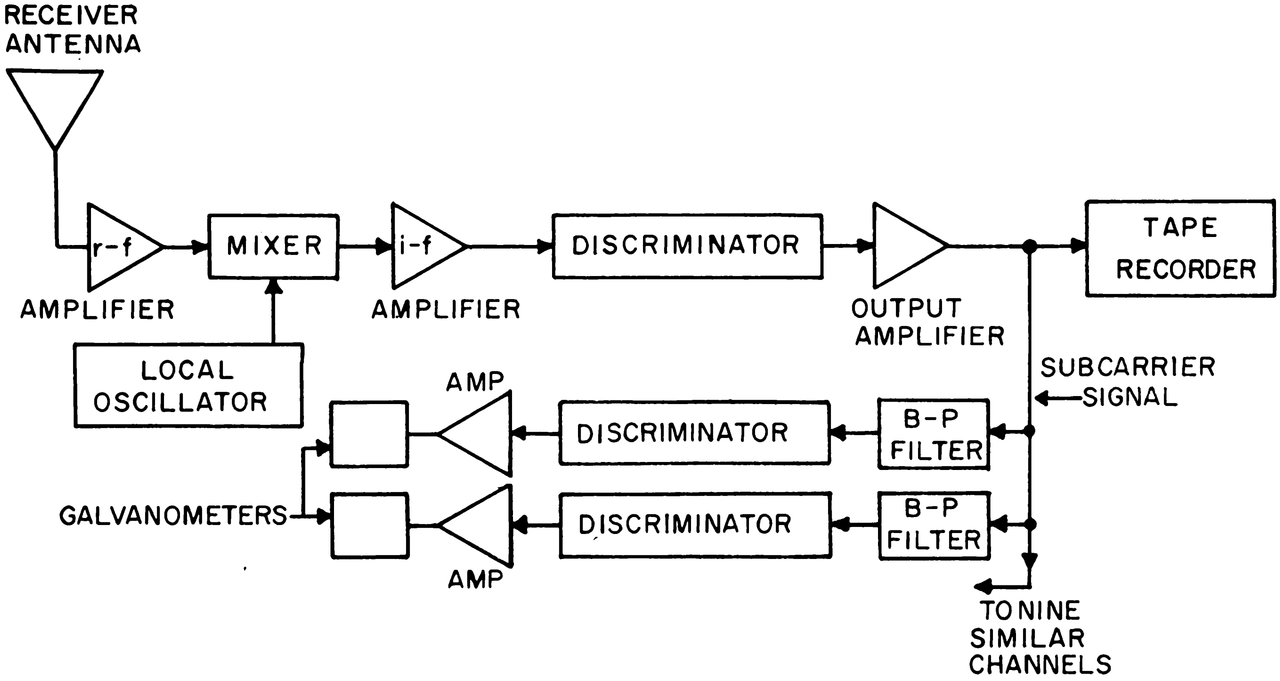

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Figure 14-8.—Telemetering receiving and recording systems, simplified block diagram.

is fed to a magnetic tape recorder and to the oscillograph circuits. The composite subcarrier signal is recorded on one of the tracks of the magnetic tape recorder. The magnetic tape provides a permanent record of all the data of the missile's flight.

The oscillograph provides a permanent graphic record of the individual items contained in the subcarrier. Therefore the subcarrier must be separated into its component parts. This process is referred to as demultiplexing.

DEMULTIPLEXER UNIT

The demultiplexer unit consists of the proper number of subcarrier discriminators, which separate and demodulate the subcarrier signals. The discriminators perform what is termed FREQUENCY DIVISION DEMULTIPLEXING in separating the frequencies into channels. Each discriminator contains a band-pass filter which allows only a narrow band of frequencies to pass. The center frequency of the band accepted by the filter in each channel corresponds in value to one of the subcarrier center frequencies.

Each subcarrier signal is then amplified and applied to a limiter circuit which removes any amplitude variations present. The resulting signal, a frequency-modulating wave of constant amplitude, is next applied to the discriminator circuit. In this stage, the frequency variations present in the signal are converted into amplitude variations. Thus, each discriminator output is a d-c voltage, the instantaneous value of which is a measure of the missile function monitored in the corresponding transmitter channel. These d-c voltages are then applied to directly coupled amplifiers and then to recording galvanometers.

GALVANOMETER OSCILLOGRAPHS

Galvanometer oscillographs are used to permanently record the missile data carried on the individual subcarrier signals (demultiplexed signals). As you know, these signals represent the end instrument data voltages. (Galvanometer oscillographs are also used to record missile data from the end instruments during missile testing prior to actual flight.)

The basic mechanism of the direct-writing oscillograph employing a D'Arsonval galvanometer is shown in figure 14-9. The instrument contains a stylus which is moved across the recording paper by the D'Arsonval assembly. (See Basic Electricity, NavPers 10086-A for information concerning this instrument.) The data voltages are applied to the coil of the galvanometer which is mounted in the field of a permanent magnet. The resulting motion deflects the stylus laterally by amounts proportional to the voltage applied. The recording paper is moved under the stylus at a constant speed by a drive motor so that the stylus traces a graph of the varying data values on the voltage-sensitive or heat-sensitive paper.

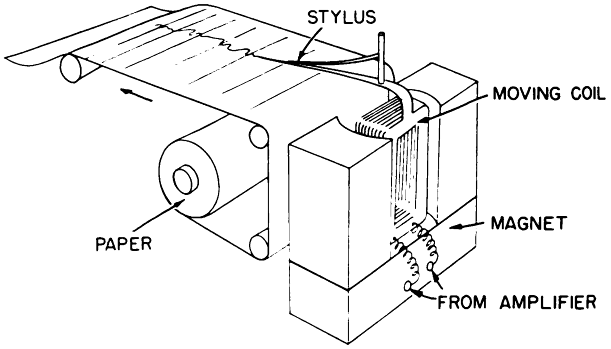

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Figure 14-9.—Basic oscillograph mechanism.

A galvanometer oscillograph employing light-sensitive paper and capable of recording several channels simultaneously is shown in simplified form in figure 14-10. This recorder contains a number of galvanometer units, each of which has a small mirror attached. Images of a light source are reflected from the mirrors onto a roll of photosensitive paper. The output voltages of the d-c amplifiers in the demultiplexer channels of the receiving equipment are connected to these elements, thereby causing them to rotate. This action deflects the light images falling on the moving light-sensitive paper, thereby producing traces which represent the variations of the data voltages.

TIMING AND SYNCHRONIZATION SUBSYSTEMS

The missile is programmed to perform certain functions and actions during its flight. The functions or actions normally depend on the passage of time as measured from a reference time, or they may depend on the occurrence of an event in the missile's program. For example, after the intent-to-launch signal is received,

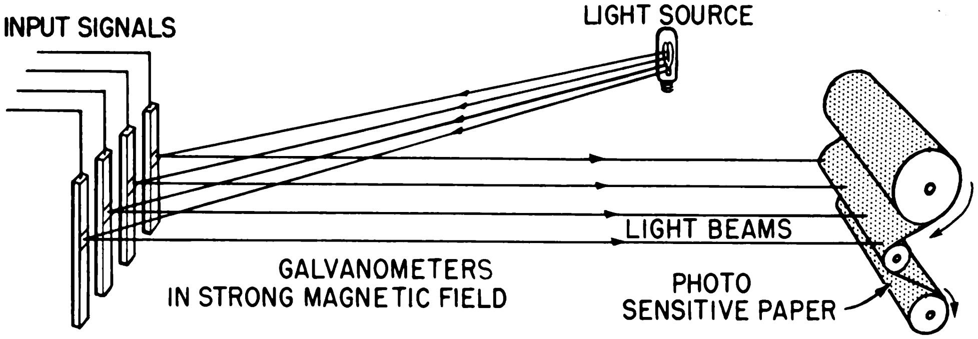

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Figure 14-10.—Principles of photosensitive galvanometer unit.

the missile needs time to condition itself for flight. Therefore, to evaluate the missile's operation, the arrival of this signal is recorded and is the reference time in the recording system for the second event, which is the initial movement of the missile, or in other words, the start of the missile's flight.

The telemetering system must measure the passage of time and record the occurrence of events within the missile. The passage of time is measured by a sine wave voltage generated within the system. The frequency of the voltage is controlled so that it takes a fixed amount of time for a cycle. (Recall that this is the same method we used in radar to measure time.) The voltage is used to drive the tapes on the recording devices and is modulated to produce timing pulses which are recorded on one of the tracks of the magnetic tape recorder. The timing pulses are a permanent record of the passage of time, and provide a common timing scale for all the units in the missile flight evaluation group.

The timing system is the basis upon which the recording system is synchronized within itself and with the missile. We have extended the definition of "synchronization" to include the correlation of (1) physical events with their recordings, (2) tape recorded information with graphic recordings, and (3) recording time with event time. Thus when evaluating the tapes you can determine when a missile was captured in the radar beam (or any other recorded event), and the exact condition of the missile at that time. You can readily deduce from the tapes the missile's velocity and attitude at that time, and whether the missile had to make a large maneuver before, during or after capture.

The time recording system has an audio voice channel which is used to record comments from an observer. Hence, the factors in the missile's flight which are not being monitored and can be observed, may be recorded so that they can be considered in the missile's flight evaluation.

THE MISS-DISTANCE SUBSYSTEM

The miss-distance subsystem provides the data necessary to calculate the miss distance between the target and the missile. This can only be done when the exercise missile flight is made against a target drone with a miss-distance transponder. The Doppler effect is used to determine the relative velocity between the target and the missile. The relative velocity is recorded on the same track of the tape recorder as the timing and synchronization subsystem signals. When the relative velocity is graphically recorded by the oscillograph, the slope of the line will indicate miss distance.

We will not go into the computation of miss distance here. Nor will we cover data reduction or analysis of a missile's flight. These are beyond the scope of this course and will be covered in a later course.

CHAPTER 15

SUBMARINE FIRE CONTROL

One of the two probable seagoing assignments for an FT(G) is duty aboard a submarine. If you are an FT(M), you may skip this chapter. But it is recommended that the FT, regardless of his specialty, who is really interested in broadening his knowledge of the fire control fields, should read and study this chapter. You will see many similarities between the underwater, gun, and missile fire control problems. The terminology may be slightly different, but the underlying fire control principle is the same in all the problem variations.

Fire control, as you well know by now, is the science of aiming a missile (projectile, guided missile, torpedo, or other destructive device) so that it will hit the target. Before we go into the underwater problem, let's take a look at the ship that carries the torpedoes.

Figure 15-1 shows what an up-to-date submarine looks like when it is on the surface. But there is more to a sub than you see in the picture. Even on the surface, a sub sits low in the water; it is both wider and deeper than you'd guess from looking at it. And of course when it is submerged you see only the slender tip of its periscope, or maybe nothing at all.

It's this invisibility that gives the submarine its principal tactical value—its ability to approach a much larger ship, deliver a lethal punch, and run—all without being seen. And there you have the key to its strategic use. The submarine can carry the fight to the enemy, even in waters where the enemy controls the surface and the air above it.

THE BASIC SUBMARINE FIRE CONTROL PROBLEM

In a discussion of the submarine torpedo fire control problem it is well to have a basic understanding of the submarine and its weapons. With the advent of nuclear propulsion, a more efficient hull design, and more advanced target detection devices and torpedoes the submarine is a more lethal weapon system than ever before. Torpedoes can now actively attack targets by changing their course, depth, and speed after launch. The fire control problem contains the same variables as before but the solution does not require the same exactness. The torpedo still must be put in the general vicinity of a target so that it will be capable of conducting its attack.

In our discussion of the fire control problem we will start with a straight running torpedo. That is the solution to the problem is a straight line course that the torpedo must follow to hit the target. Aiming such a torpedo so that it will strike a moving target is similar to the problem encountered in gun and guided missile fire control. The target moves across the line of sight, and a torpedo aimed directly at the target will miss because the target moves as the torpedo travels from the tube toward the intended victim. Thus it is necessary to fire ahead of the target to hit it.

The gun projectile and the torpedo have the same objective so it is interesting to compare the factors that affect the paths of these missiles. The ship on which the guns are mounted is moving forward, and it may be pitching and rolling as well. The target itself is moving. If it's an aircraft, it may be moving hundreds of feet each second. The path of the projectile, from gun to target, depends on many things. Here are some of them: the kind, weight, and temperature of the propellant charge; the force and direction of the wind, both at sea level and high in the air; the pressure of the atmosphere; and the "drift" of the projectile due to its rotation.

To all of these factors you add the motion of your own ship, and the range, course, and speed of the target. The gun fire control system absorbs all that information, and comes up with an answer. What does the answer consist of?

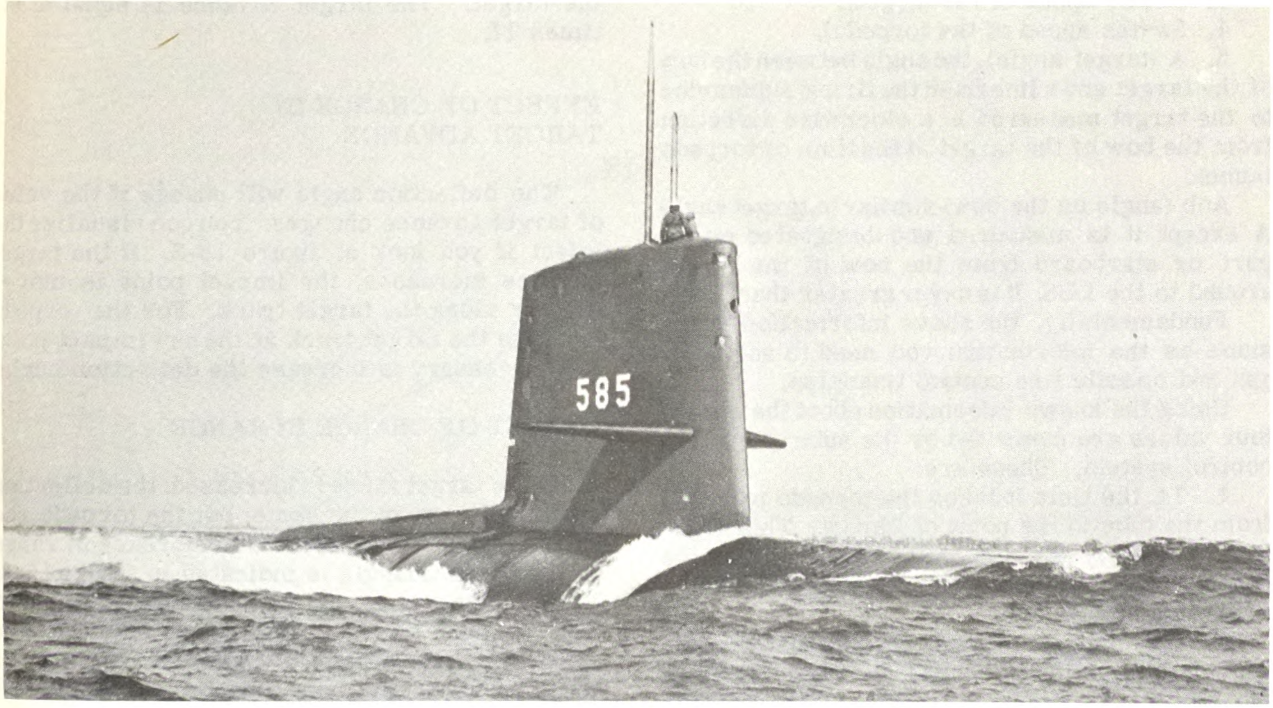

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Figure 15-1.—Submarine underway on the surface.

As you know, it consists of two parts. If the projectile is to fall on the target, rather than to the right or left of it, you must have the proper gun train angle. If the projectile is to fall on the target, rather than beyond it or in front of it, you must have the proper elevation angle. So, for a gun, the solution to the fire control problem, at any given instant, is two angles.

In some ways the submarine torpedo fire control problem is even harder. First of all, you can't train the tubes the way you do a gun. The underwater tubes are immovably fixed to the hull. Second, a torpedo moves a lot slower than a projectile. During the torpedo run, the target may move a considerable distance. And that means you must lead it by a large angle.

The basic solution to the torpedo fire control problem has only one primary part. It is deflection angle, although it is not always called that.

Figure 15-2 shows the basic torpedo triangle for straight fire. Straight fire means that no maneuvers are required of the torpedo during its run from the launching tube to the target. To solve the straight fire triangle, the following information must be known.

1. R (range), the distance from the firing submarine to the target at the time of launch.

2. Br (relative target bearing), the angle between the firing submarine's bow and a line drawn from the submarine to the target (LOS) measured in a clockwise direction from the submarine's bow at the time of torpedo launch.

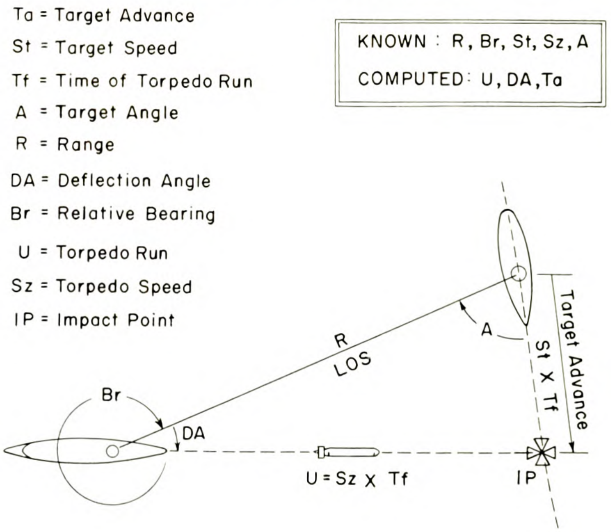

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Figure 15-2.—Basic underwater fire control triangle (straight fire).

3. St (the speed of the target).
4. Sz (the speed of the torpedo).
5. A (target angle), the angle between the bow of the target and a line from the firing submarine to the target measured in a clockwise direction from the bow of the target at the time of torpedo launch.

Aob (angle on the bow) similar to target angle A except it is measured and designated either port or starboard from the bow of the target around to the LOS. It is never greater than 180°.

Fundamentally, the above information is the same as the information you need to solve the gun and missile fire control triangles.

Using the known information about the target, four values are computed by the submarine fire control system. These are:

1. Tf, the time it takes the torpedo to travel from the tube to the point of impact. This value is not used by the torpedo but is needed by the fire control system to compute torpedo run and deflection angle.
2. StTf (target advance), the distance the target travels while the torpedo is traveling from the tube to the point of impact. This value is not used by the torpedo but is needed to compute the torpedo run and deflection angle.
3. U (torpedo run), the distance the torpedo travels from the tube to the impact point.
4. DA (deflection angle), the angle between a line from the firing submarine to the target (LOS) at the time of launch and a line from the firing submarine to the point of impact (line of fire). The deflection angle is the lead or prediction angle.

HOW TO FIND TARGET SPEED AND TARGET ADVANCE

If a car travels 50 miles per hour for 3 hours, you know that it has traveled 150 miles. You get the distance it travels by multiplying the speed of the car by the time it was on the road. The same rule applies to a torpedo. By multiplying the torpedo speed, Sz, by the time it travels, Tf, you get U—the distance the torpedo travels. This is called torpedo run.

The same kind of reasoning applies to target advance. This value can be found by multiplying the target speed by the time it takes the target to travel from the point it occupied at torpedo launch to the impact point. This time is the same as the time the torpedo takes to get to the impact point, if the torpedo is to collide with the target. The target advance is equal to St. times Tf.

EFFECT OF CHANGE IN TARGET ADVANCE

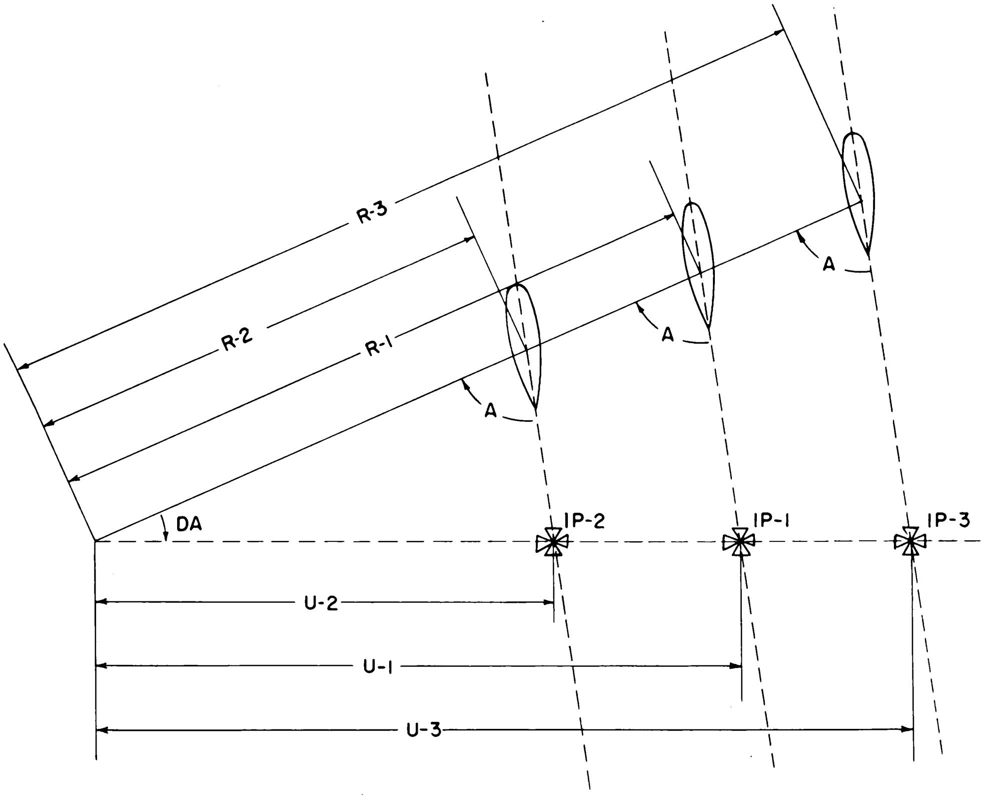
The deflection angle will change if the value of target advance changes. You can visualize the effect if you look at figure 15-2. If the target advance increases, the impact point is moved further along the target track. For the torpedo to cross the target track at the new impact point it is necessary to increase the deflection angle.

EFFECT OF CHANGE IN RANGE

If the target range is increased, the deflection angle will remain the same, but the torpedo run will increase. The effect of an increase in range on the basic triangle is indicated in figure 15-3. Target advance, as you just learned, is equal to $Sz \cdot Tf$. Also, torpedo run is equal to $Sz \cdot Tf$. The ratio of target advance, (which is one side of the triangle) to torpedo run, (which is another side) is then $St \cdot Tf/Sz \cdot Tf = St/Sz$. Since for any particular fire control problem Sf and St are constants, the ratio St/Sz is a constant, and the ratio of target advance to torpedo run is a constant. As the range increases, the target advance and the torpedo run increase in proportion. This leaves the deflection angle always the same if range increases but A remains unchanged.

EFFECT OF CHANGE IN TARGET SPEED

If the target speed is changed, both U and DA may change. The effect of changes in target speed are shown in figure 15-4. As St increases, the impact point moves forward along the target track. This means that DA becomes larger. This is true for any values of R, Br, or A. In the situation shown in figure 15-4, U also has increased. This is true if, at the time of impact, the torpedo is catching up with the target. That is, the angle between the bow of the target and the torpedo track, measured from the bow of the target in a clockwise direction, is between 90° and 270°. If the target is coming toward us, then an increase in speed will lengthen target advance and bring the impact point closer to the firing submarine. In this case, U will be shorter. These situations are reversed if target speed is reduced.



NOTE: *Lead triangle shape results from ratio of* $\frac{St}{Sz}$ *and is independent of range.*

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Figure 15-3.—The effect of range.

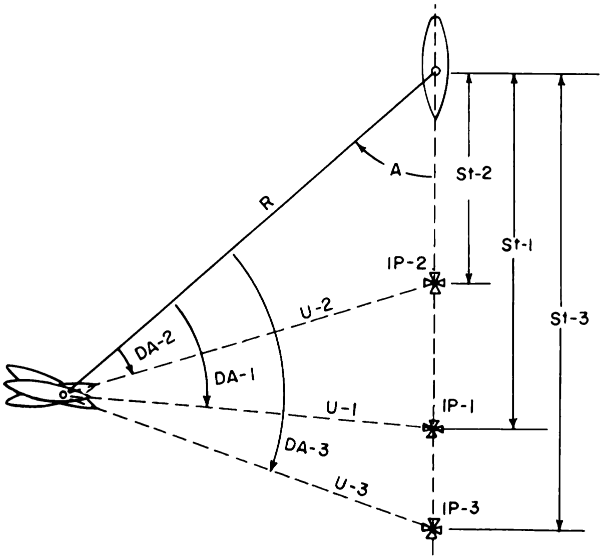

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Figure 15.-4.—The effect of change in target speed.

EFFECT OF CHANGE IN TARGET ANGLE

Target angle (A) is an indirect measurement of target course. Thus a change in A will cause a change in the impact point and effect both U and DA. This is shown in figure 15-5A and B. In figure 15-5A the target is in the center of a circle which is divided into quadrants. Target speed is constant in the illustration and a line is drawn to the firing submarine. The effect of target angle changes on U and DA is shown vectorially by the vectors marked U and DA.

In figure 15-5B the impact point (IP) is shown for three target angles. In these three examples the target is heading toward the firing submarine. Notice how U and DA vary with A.

EFFECT OF CHANGE IN TORPEDO SPEED

The speed of the torpedo affects both U and DA. Refer to figure 15-6 to see the effect. If

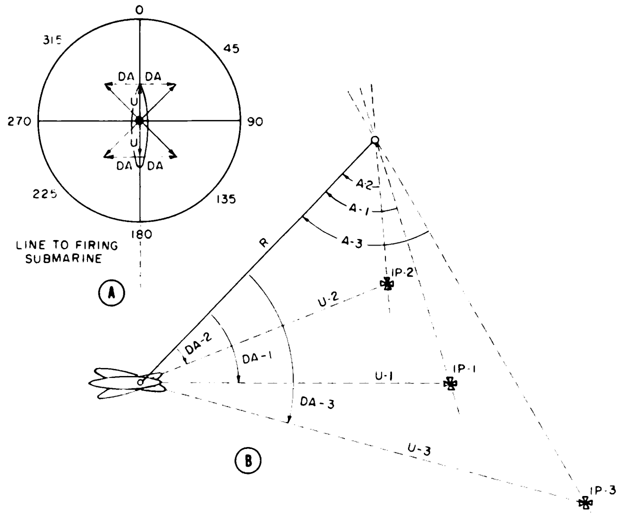

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Figure 15-5.—The effect of target angle.

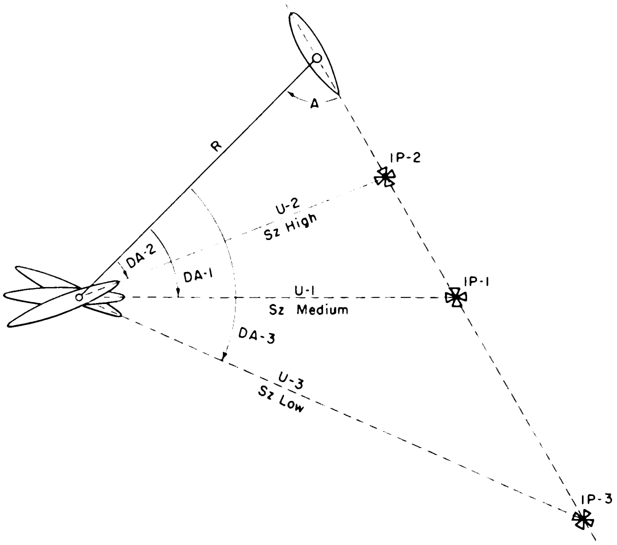

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Figure 15-6.—The effect of torpedo speed.

the torpedo speed increases, Tf decreases. This means that the target advance decreases and the impact point moves back along the target track. Notice too that the deflection angle and U also decreases because Tf has decreased.

CURVED FIRE

The previous discussion has been based on the assumption that the firing submarine was aimed at the impact point at the time of torpedo launch and that the torpedo ran straight to the impact point. With the development of a means to preset a course to steer into the torpedo the submarine no longer had to be on a prescribed heading and is free to maneuver. Upon firing, the torpedo leaves the tube, makes a short run, then turns to its preset course, and heads for the impact point.

This action is shown in figure 15-7. As you can see, the torpedo run has been increased. When the torpedo left the tube it was actually moving away from the impact point. Therefore, the torpedo has an additional distance to run. Also, since Tf has been increased the target advance has been increased, modifying U still further. The deflection angle has lost its significance. To determine the angle through which the torepedo must turn to reach the impact point, the computer solves for the angle between the torpedo track and the bearing line (LOS). This value is G_1 - Br and is termed the solution angle. This angle is roughly equivalent to deflection angle.

BASIC TORPEDO BALLISTICS AND CORRECTIONS

The torpedo is fired under varying conditions and at different locations in the world. These changes in environment affect its speed and direction of run. Since torpedo speed and direction are important quantities used in the computation of the fire control problem, the forces which affect the course and speed of the torpedo must be corrected for in the computer.

FORCES AFFECTING TORPEDO SPEED

The nominal speed of a torpedo is that average speed which occurs during a normal run. This run must be taken at standard depth and at standard sea water temperature.

The nominal speed of a torpedo is established at a standard sea water temperature of 62°F. As the temperature of the water changes, its pressure and density change, which will affect the speed of the torpedo.

The nominal speed of a torpedo is established at a particular running depth. If fired at a greater depth, the density of the water may be higher because of lower temperature. Therefore the torpedo will be slowed down. This decrease must be considered in the computer.

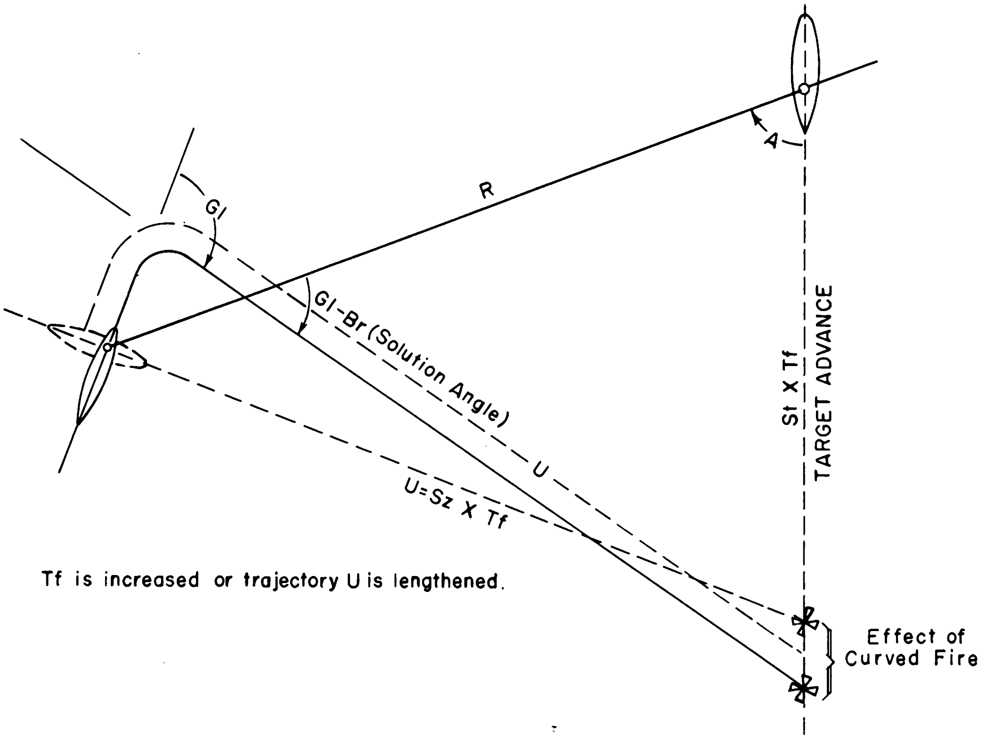

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Figure 15-7.—Basic underwater fire control triangle (curved fire).

If the torpedo climbs or dives to a depth different from which it is fired, the change in depth will have an effect on its speed.

Often a torpedo is ejected from the tube at a different speed than its final speed. It takes a definite length of time before the final speed is reached, and during that time it will cover a part of its total run. This effect of the changed speed must, of course, be considered by the computer.

FORCES AFFECTING TORPEDO COURSE

The torpedo, when in the water, is steered by a directional gyro which will retain its spin axis in a predetermined direction unless acted upon by outside forces. An angular position is set into the gyro before firing, and the rudders of the torpedo are controlled by this setting.

CORRECTIONS TO TORPEDO SPEED AND DIRECTION

Corrections to nominal speed for a particular weapon is referred to as jSz. Every torpedo is designed with a definite theoretical running speed. If, after many torpedoes have been produced and tested, this speed is found to differ from the design speed, a correction must be made before firing. Since the torpedo under actual conditions will operate at different sea water temperatures, a correction must be made for the difference between the existing temperature and the standard (62° F). A correction should also be made for the temperature of the battery electrolyte in battery-driven torpedoes. A change in the electrolyte temperature changes the power output of the battery, and that will change the torpedo speed.

Ordered Depth Correction

The symbol jSzh describes an ordered depth correction. Very often torpedoes are fired at depths other than their tested depths, as for instance when firing at another submarine. Sometimes improvements are made in a torpedo during the course of manufacture, making it possible to attain greater depths than the original designed depth. In these cases, the nominal speed of the torpedo must be changed to consider the difference between the standard depth and the actual firing depth.

Depth-Change Run Difference

Ky is the symbol for depth-change run difference (fig. 15-8). When a torpedo is fired and observed to run at a depth which is above or below the torpedo tube depth, its speed will be changed because of the effect of gravity. If a torpedo has to rise to a lesser depth, it will be slowed down (just as a projectile or missile will) and cover less distance in a given period of time. On the other hand, a torpedo going down to a greater depth will be helped by gravity, and will therefore go faster and cover a greater distance.

Emergence Factors-Run Difference

Uy symbolically describes emergence factors-run difference (fig. 15-9). If a car travels at 50 miles per hour for 3 hours, it will cover 150 miles. If it went faster, it would obviously go farther in the same 3 hours. In the same way, if a torpedo emerges from a torpedo tube at a speed greater than its running speed, in a certain period of time it will go farther. This additional distance must be allowed for in the computer. On the other hand, if a torpedo emerges from the tube at a speed lower than its running speed, that is, swims out, it will cover a shorter distance in a given period of time.

DIRECTIONAL ERRORS

It was mentioned earlier that torpedoes use a gyro to provide a directional reference. A gyro, because of its momentum when spinning at a high speed, will remain directionally rigid unless acted upon by external forces. Because of this rigidity, it is used as a stable reference for torpedo azimuth (direction control).

The following discussion provides a brief review of the effect of earth's rotation on a gyro. Keep in mind that the gyro described here has its axis parallel to the earth's surface, rather than perpendicular to the horizontal as in a vertical gyro.

Now back to the torpedo's gyro. Every day the sun APPEARS to rise in the east and set in the west. It only appears this way, because the earth is rotatin on its own axis from west to east, and makes a complete rotation once every 24 hours.

Since the earth rotates, while the gyro in the torpedo remains fixed in space, the direction in which the gyro seems to point changes at the rate that the earth is turning. This appears as an apparent drift (precession) of the gyro and occurs at the rate the earth is turning-15° per hour. See figure 15-10.

The relative alignment of the gyro's spin axis with the earth's spin axis causes different apparent drift rates as shown in figure 15-10. The maximum effect on a directional gyro takes place at the North or South Pole, where the spin axis of the gyro is at right angles to the earth's spin axis. At the Equator, the spin axis of the gyro is parallel to the earth's spin axis, so that the rotation of the earth has no effect on the gyro. At intermediate latitudes, the earth's rate (angular velocity) effect varies as the sine of the latitude. In these cases the gyro spin axis is tilted at the angle of latitude with respect to the earth's spin axis.

Since the earth turns at a constant rate, it is possible to put a constant correction on the gyro which will cause the gyro to counteract the effect of drift at any given latitude (fig. 15-11). This correction, put into the torpedo at the test run site, is called proofing latitude.

Look at figure 15-12. Two torpedo paths are shown. In part A, a torpedo with its gyro compensated for apparent drift is aimed at point P. Point P turns with the earth from T_1 to T_2 while the torpedo is traveling toward it. The torpedo's gyro senses earth's movement and attempts to stay aligned with the space reference. However, since a correction for apparent drift has been applied to the gyro to compensate for earth's rotation it remains directed toward point P. Therefore the torpedo travels a straight path to point P.

In part B of figure 15-12 the same situation is illustrated. Now, however, an uncompensated gyro is steering the torpedo. The gyro will sense earth's rotation and apparently precess to remain aligned with the space reference. The torpedo will follow a curved path with respect to the earth and will miss point P. This curved path is typical of many fire control firings and introduces the need for latitude corrections which can be inserted into the computer to adjust gyro angle accordingly.

The corrections are detailed in figure 15-13. A difference of latitude between firing and proofing causes the torpedo to turn away

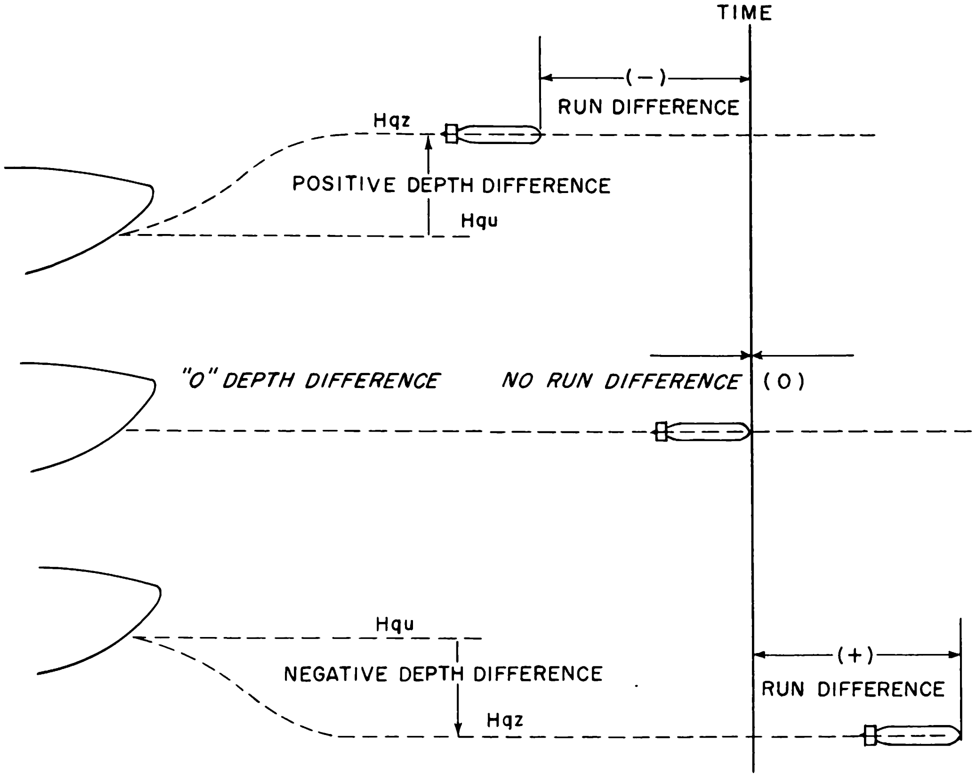

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Figure 15-8.—Depth change run difference (Ky).

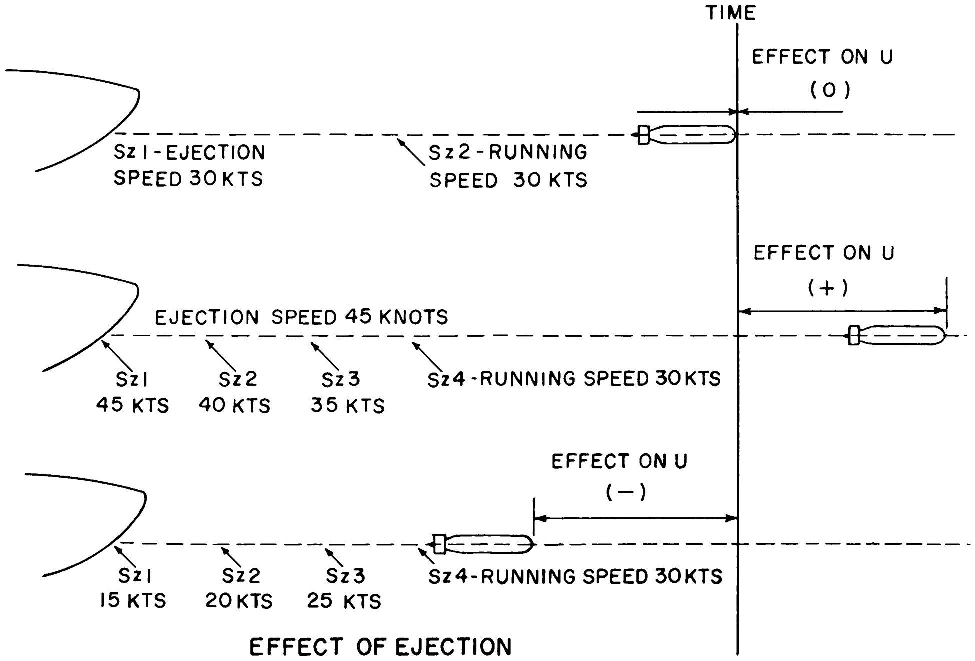

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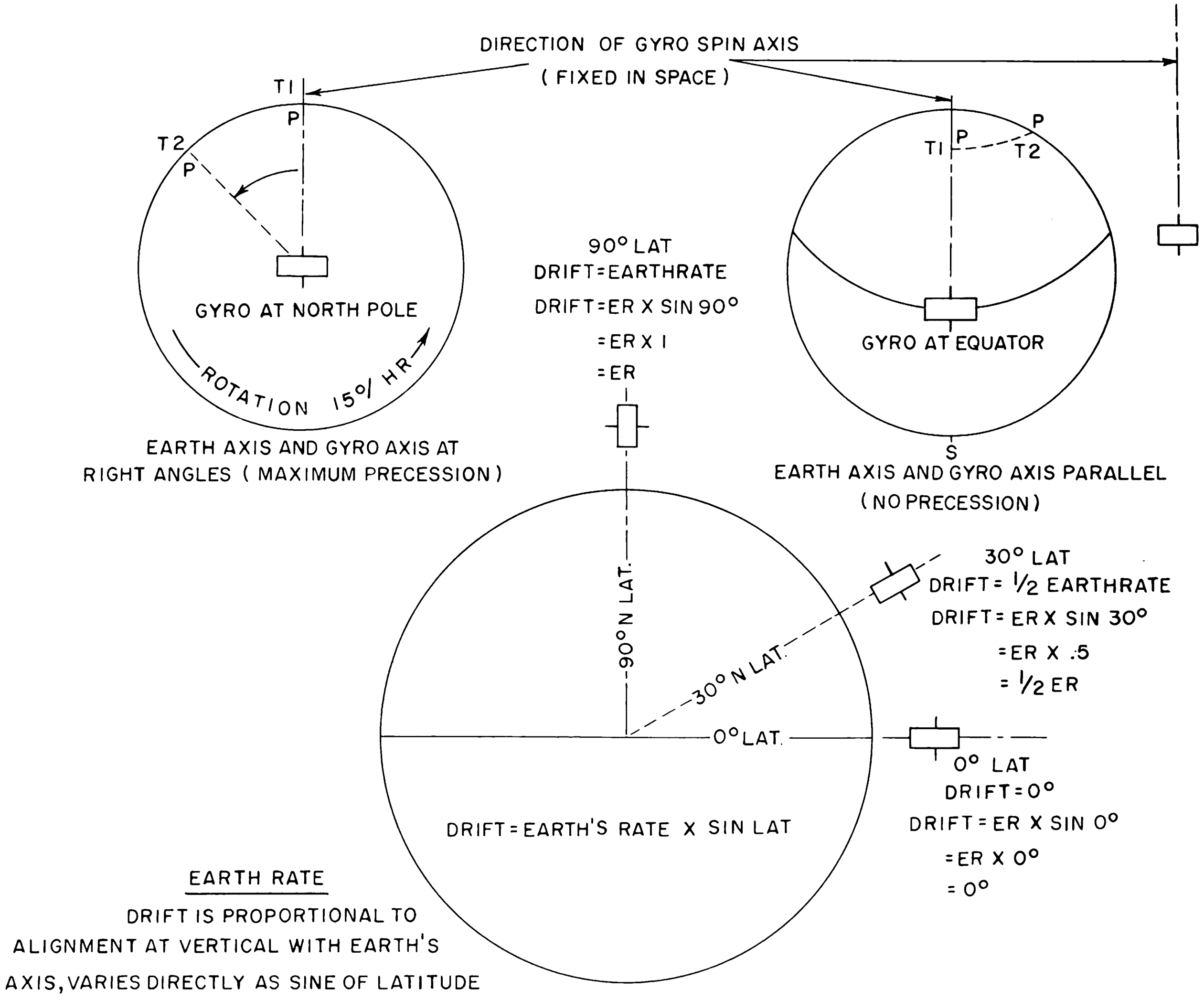
Figure 15-9.—Emergence factors—run difference.



LATITUDE EFFECT

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Figure 15-10.—Gyro drift (apparent precession).

from the impact point during torpedo run. At the end of the run, the torpedo will have a heading difference equal to the drift rate of the gyro (DjGm) times the time of flight (Tf). If an imaginary effective path from own ship to the end of U is drawn along with a line tangent to the curve at the end of the actual U and extended back across the calculated U, a triangle is formed. The heading difference will be equal to twice the latitude error angle (angle between the calculated track and effective path). Since Gm (latitude correction) must balance out the latitude error, it follows that Gm = 1/2DjGm x Tf.

Figure 15-14 shows a typical shot with latitude correction (Gm) inserted into the fire control problem to balance out latitude error. Note that latitude correction changes DA by an amount equal to latitude error.

BASIC TORPEDO TRAJECTORIES

A knowledge of the basic torpedo trajectories will help you toward a better understanding

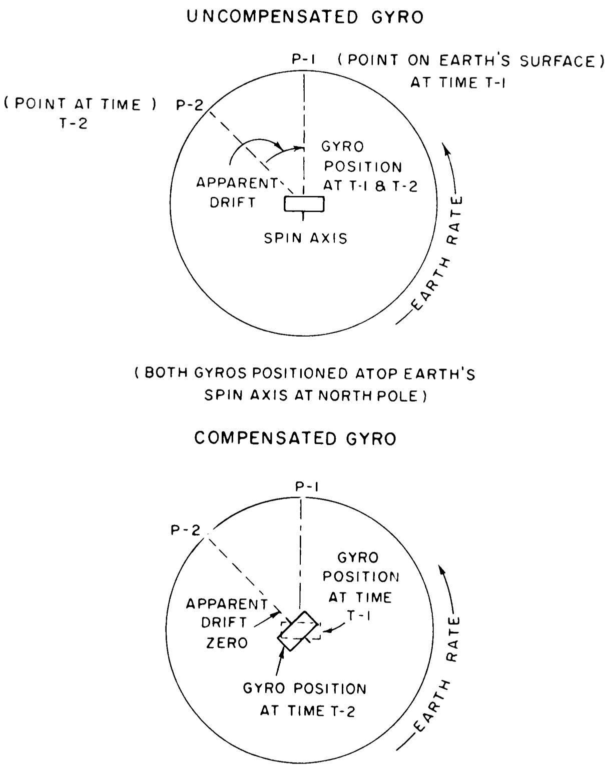
UNCOMPENSATED GYRO
P-1 (POINT ON EARTH'S SURFACE) AT TIME T-1
(POINT AT TIME T-2) P-2
GYRO POSITION AT T-1 & T-2
APPARENT DRIFT
SPIN AXIS
EARTH RATE
(BOTH GYROS POSITIONED ATOP EARTH'S SPIN AXIS AT NORTH POLE)
COMPENSATED GYRO
P-1
P-2
GYRO POSITION AT TIME T-1
APPARENT DRIFT ZERO
GYRO POSITION AT TIME T-2
EARTH RATE

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Figure 15-11.—Compensation effect on drift.

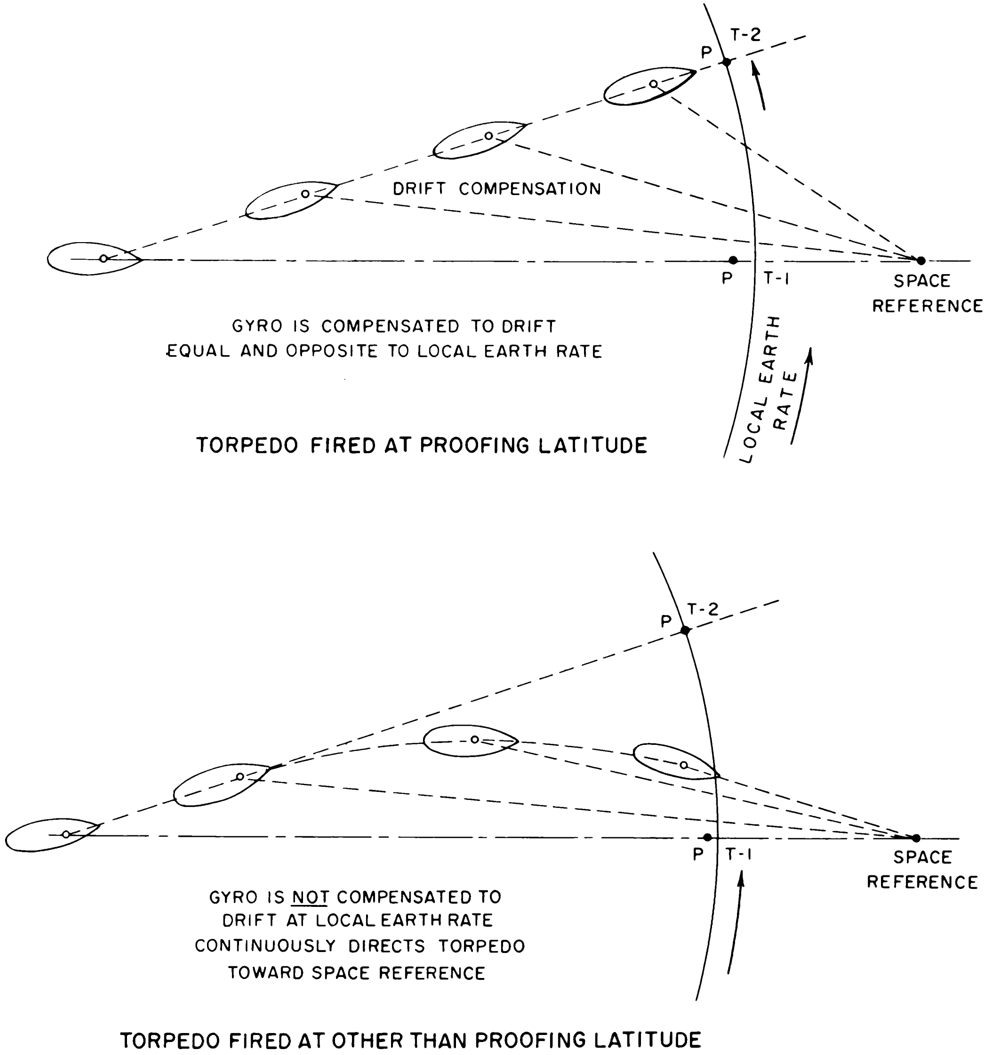
T-2
P
DRIFT COMPENSATION
P
T-1
SPACE REFERENCE
GYRO IS COMPENSATED TO DRIFT EQUAL AND OPPOSITE TO LOCAL EARTH RATE
LOCAL EARTH RATE
TORPEDO FIRED AT PROOFING LATITUDE
P
T-2
P
T-1
SPACE REFERENCE
GYRO IS NOT COMPENSATED TO DRIFT AT LOCAL EARTH RATE CONTINUOUSLY DIRECTS TORPEDO TOWARD SPACE REFERENCE
TORPEDO FIRED AT OTHER THAN PROOFING LATITUDE

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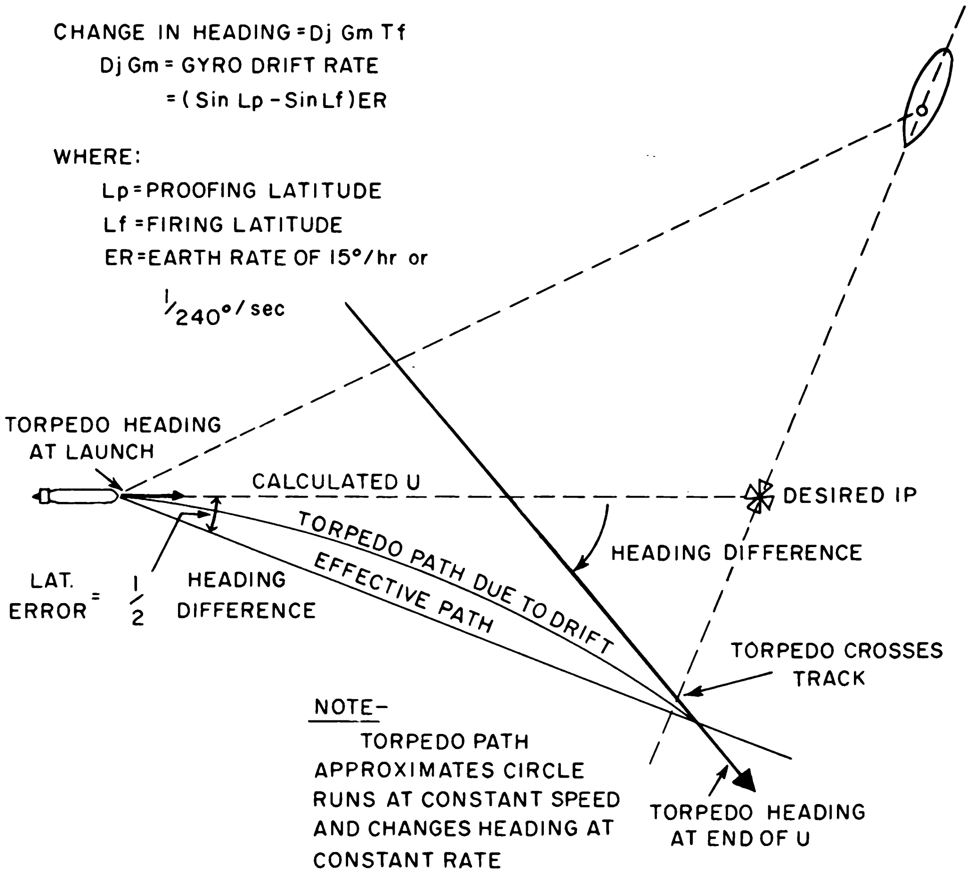
Figure 15-12.—Effect of gyro drift on torpedo course.


CHANGE IN HEADING = Dj Gm Tf
Dj Gm = GYRO DRIFT RATE
= (Sin Lp - Sin Lf) ER
WHERE:
Lp = PROOFING LATITUDE
Lf = FIRING LATITUDE
ER = EARTH RATE OF 15°/hr or
1/240°/sec
TORPEDO HEADING AT LAUNCH
CALCULATED U
DESIRED IP
TORPEDO PATH DUE TO DRIFT
EFFECTIVE PATH
HEADING DIFFERENCE
LAT. ERROR = 1/2 HEADING DIFFERENCE
TORPEDO CROSSES TRACK
NOTE-
TORPEDO PATH APPROXIMATES CIRCLE RUNS AT CONSTANT SPEED AND CHANGES HEADING AT CONSTANT RATE
TORPEDO HEADING AT END OF U

55.279

Figure 15-13.—Latitude difference effect on torpedo course.

of the general submarine fire control problem. The basic fire control problem as explained previously, involves a preset, straight running torpedo as shown in figure 15-15. The diagram displays information describing the target position related to own ship. This information is Br, R, and A. The target advance is shown in figure 15-15, by St · Tf. Information related to the target is referenced to the fire control reference point on own ship. The torpedo tubes are forward of the reference point by a distance Pl. The torpedo is launched from the tube and runs straight, a distance M called the REACH DISTANCE. It then turns through an angle (G_1, the gyro angle) with a turn radius of Z_1, and runs straight to the impact point. The angle between the torpedo track and the bearing line is G_1 - Br, the solution angle. The angle between the target track and the torpedo run is designated I and is called the impact or track angle which is equal to G_1 - Br + A.

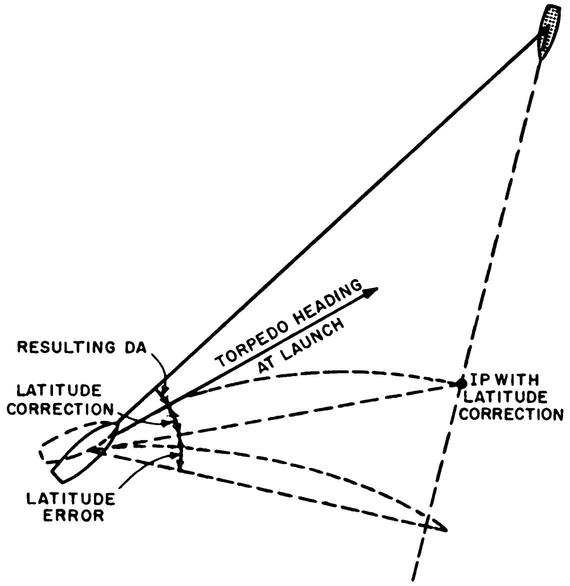


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Figure 15-14.—Effect of latitude correction.

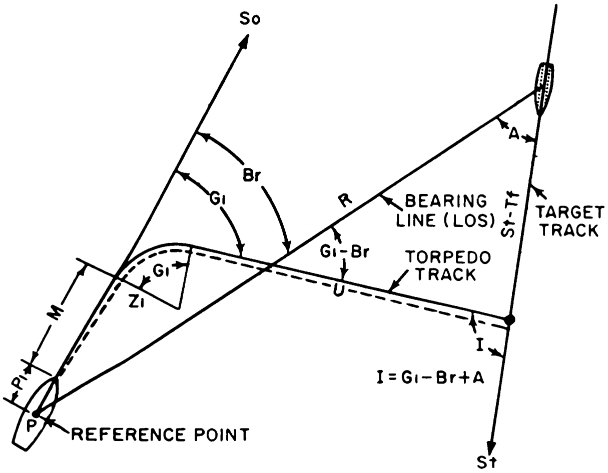

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Figure 15-15.—Preset torpedo on a straight run.

Another type of torpedo is the homing torpedo. As shown in figure 15-16 this torpedo will search for the target by SNAKING, that is, turning left and right in order to "hear" the target. It is desirable to have this type of torpedo enable, that is, start to search, before crossing the target track. To accomplish this the fire control problem is solved in the normal way for U. Then a value of Ue off. (enabling run offset) is subtracted from it and transmitted to the torpedo. This will cause the torpedo to enable before crossing the target track with the torpedo aimed at the intercept point. Except for Ue offset, then, the trajectory for a homing torpedo is the same as for the straight run shot previously described.

Some torpedoes turn a second time when they are close to the target. The second turn has two advantages: (1) the torpedo may cross the target track twice increasing its opportunities to detect the target, and (2) the angle at which the torpedo crosses the target track is improved. Consider a case where the target is coming toward you. A preset straight running torpedo sees only the width of the target. However, a second turn torpedo can turn and cross the target track at right angles. It sees the length of the target and as a result has a higher hit probability.

Sometimes it is desirable to fire torpedoes in salvos. In this case they are not fired all at the same point. To allow for errors in our knowledge about the target, or for possible changes in target course and speed, the torpedoes are fired in a pattern. One such pattern is linear spread. A unit of linear spread is selected for each torpedo. A number of units is selected either fore or aft. Look at figure 15-17. Here three impact points are shown. The center impact point is the one for no linear spread. Leu on the diagram represents the distance selected for a unit of spread. The impact point further along the target track represents the impact point with two units of spread forward in the computer. Notice that linear spread is put in along the target track.

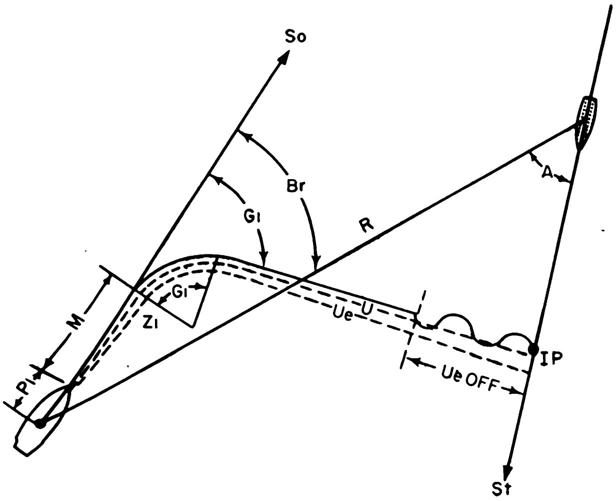

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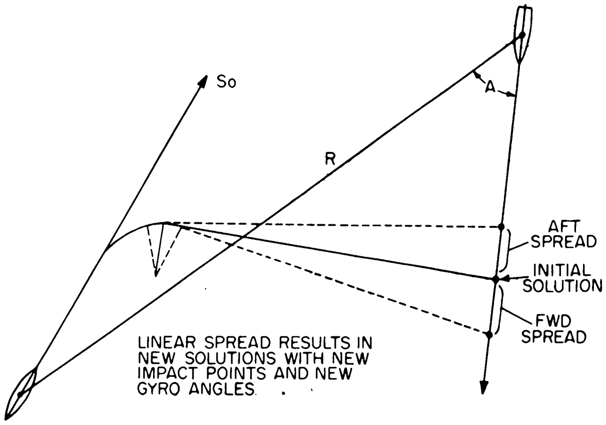
Figure 15-16.—Preset torpedo on a homing run.


So
A
R
AFT SPREAD
INITIAL SOLUTION
FWD SPREAD
LINEAR SPREAD RESULTS IN NEW SOLUTIONS WITH NEW IMPACT POINTS AND NEW GYRO ANGLES.

55.283

Figure 15-17.—Preset torpedo with linear spread.

Both gyro angle and torpedo run are changed by linear spread. Linear spread clearly will increase hit probability if there is an error in estimating target speed.

Another type of salvo pattern is called angular spread. As with linear spread, a unit of spread is selected. Then for each torpedo, a number of units is selected either right or left. See figure 15-18. The spread angle is added or subtracted to gyro angle after a solution has been reached. As a result, the torpedo run (U) is unchanged. Angular spread is a correction across the torpedo track. Linear spread is a correction along the target track. Either correction is intended to allow for errors in the knowledge about the target or for errors in the torpedo.

Torpedoes which can be ordered to run at a certain depth and then search for a target by acoustical means may be dangerous to own ship should own ship be at or near the search depth. Torpedoes are instructed to search above or below a certain depth, called stratum depth. If own ship is in the depth range in which the torpedo will search, then the computer will give a warning to this effect. Refer to figure 15-19. Do is the depth of the keel of own ship. A torpedo which will search below a certain depth is referred to as a torpedo running below stratum. In this case, a safety factor is added to own depth and any depth below this is considered safe. A torpedo which will search above stratum depth is referred to as a torpedo running above stratum. In this case the height of own ship (plus a safety factor) is subtracted from own depth to determine the safe level of search.

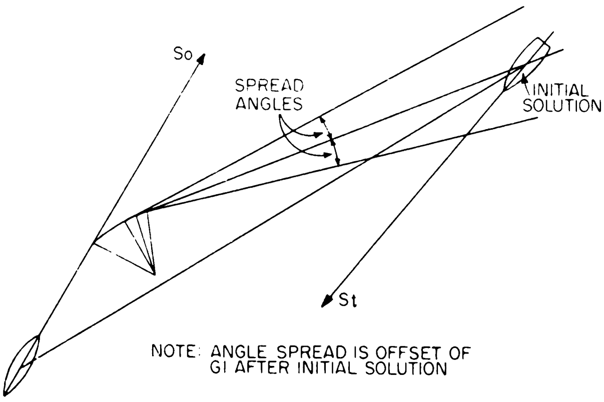


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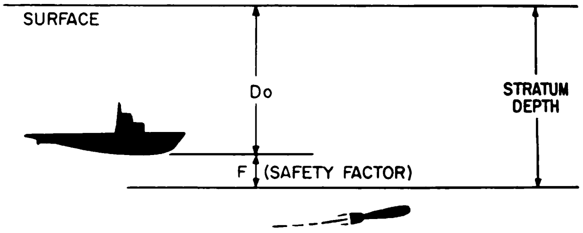
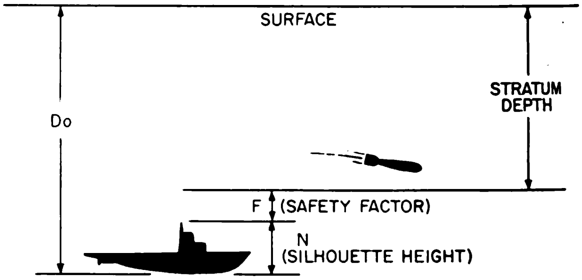
Figure 15-18.—Preset torpedo with angular spread.



TORPEDO RUNNING BELOW STRATUM



TORPEDO RUNNING ABOVE STRATUM

55.285
Figure 15-19.—Stratum relationships.

It can be seen that the torpedo's search pattern is limited by stratum depth. The stratum establishes the upper or lower depth at which the torpedo will search. The depths between which the torpedo will search is called stratum limit.

EVOLUTION OF UNDERWATER FIRE CONTROL SYSTEMS FROM WW II TO PRESENT

The solution of the underwater fire control problem requires that relative position (range and relative bearing), course, and speed of the target be determined so that relative torpedo course (gyro angle) can be computed to direct a torpedo to an intercept point along the target track. The determination of target information is complicated because, in general, only intermittent observations of the target are possible. The problem of position keeping is solved by using the technique of setting up a phantom problem just as we do in a surface fire control rangekeeper or computer. This technique provides the continuous information needed for the computation of the lead necessary to hit a moving target.

Before computers came into use, plots and slide rule devices were used to determine the torpedo course necessary to hit the target. This method placed limitations on how the attacking submarine could maneuver because the solution had to be worked out in advance of the actual firing. The submarine was then maneuvered to the proper position and heading (proper lead angle) and waited until the target reached a certain point along its track before firing the torpedo. This procedure, necessary with nonsteerable torpedoes, was continued in use where steerable (but not always reliable) torpedoes were fired with zero gyro angles.

The need for continuous (sometimes the term synchronous is used) solutions to take advantage of the steerable torpedoes led to the development of computers. With continuous solutions, the submarine was freed of the necessity of being in a particular place, at a particular time, on a particular heading, to launch a torpedo. Torpedoes could now be launched if the target data was considered reliable and the run within the torpedo capabilities.

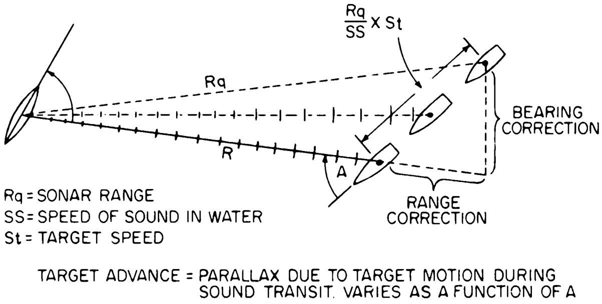
Electrically set torpedoes further eased the problems of launching because the weapons could be made to follow continuously (synchronously). the solution generated in the fire control system. Thus, a correct solution is in the torpedo at any instant.

Homing torpedoes further freed firing submarines of restrictions because less exact solutions could be used and the homing capability of the torpedo would compensate for the solution errors. However, homing torpedoes had to be programmed before firing and a means of inserting these instructions (preset instructions) had to be incorporated into the fire control system.

Along with torpedoes, the development of detection equipment, gyrocompasses, and other sensing devices has had its effect on the evolution of underwater fire control equipment. Most notable is the need for converters of sonar information. Such coverters for sonar bearings appeared in the earliest submarine fire control computers, called torpedo data computer (TDC). There are several reasons why sonar data conversion is necessary. First, sonar bearings and ranges are measured from the point at which the sonar head is located. This point is displaced from the fire control reference center on most ships. The effect of this displacement on sonar range and bearing will vary as a function of relative target bearing.

Another factor affecting passive sonar data is the distance measured from the target sound source (screws) to the center of the target. This distance is dependent on target size and varies as a function of target angle.

A final factor affecting sonar measured quantities is target advance during sonar ranging. Figure 15-20 illustrates the range and bearing corrections due to target advance while the sonar is ranging. The corrections vary as a function of target angle.


$\frac{Rq}{SS} \times St$
Rq
R
A
BEARING CORRECTION
RANGE CORRECTION
Rq = SONAR RANGE
SS = SPEED OF SOUND IN WATER
St = TARGET SPEED
TARGET ADVANCE = PARALLAX DUE TO TARGET MOTION DURING SOUND TRANSIT. VARIES AS A FUNCTION OF A

55.286

Figure 15-20.—Target advance affects sonar data.

The series of fire control systems described below shows how the evolution of the systems paralleled the evolution of the weapons.

The first of the underwater fire control computers was the TDC mentioned previously. Figure 15-21 is a block diagram of the TDC Mk 4. The TDC is a position keeper and a gyro angle solver. In fact, it has two angle solvers which provide separate solutions for the forward and after torpedo tubes simultaneously. Even in this early computer a sonar bearing converter is provided. Gyro angle is transmitted electrically to the torpedo room, but it must then be inserted mechanically into the torpedo.

The TDC had certain functions added to it and became the FCS Mk 106 Mod 5 (Fig. 15-22). In this system, gyro angle is transmitted continuously to the electrically set torpedoes. Enabling run and ordered depth are transmitted electrically to the torpedo. The insertion of preset functions for homing torpedoes is made a a control panel. The automatic transmission of synchronous functions requires a monitoring system to indicate whether or not

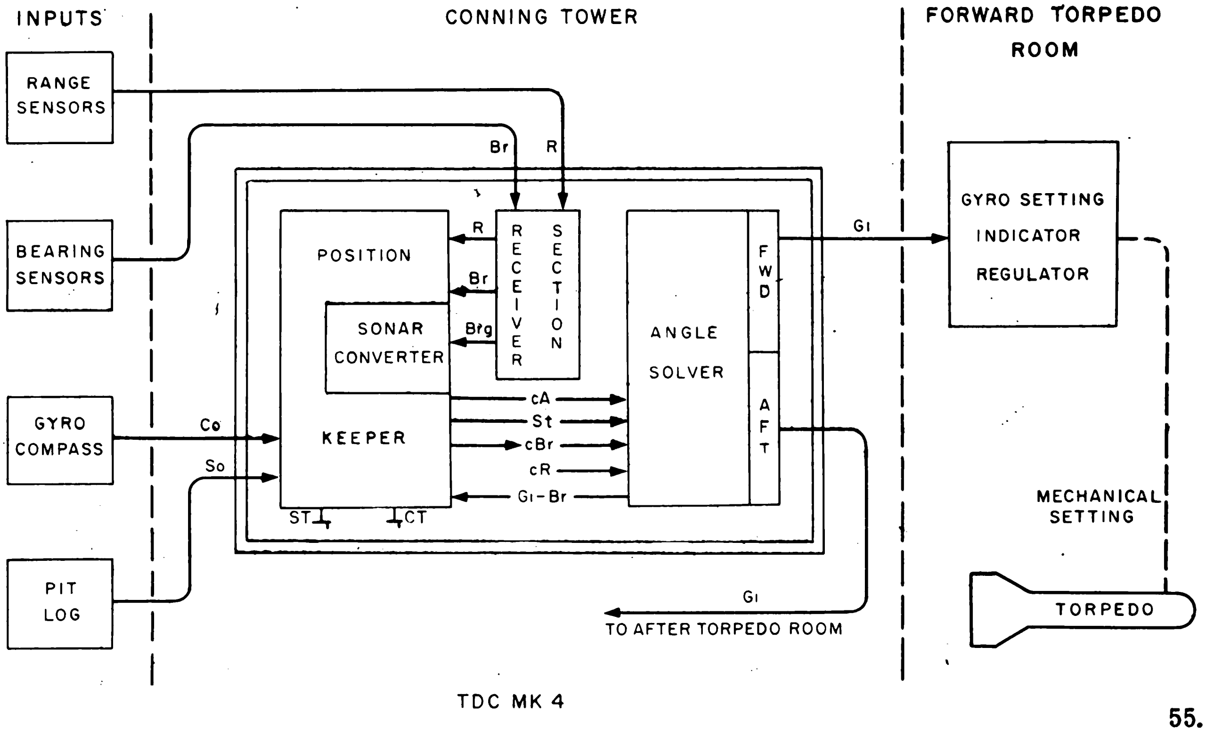


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Figure 15-21.—Torpedo data computer simplified block diagram.

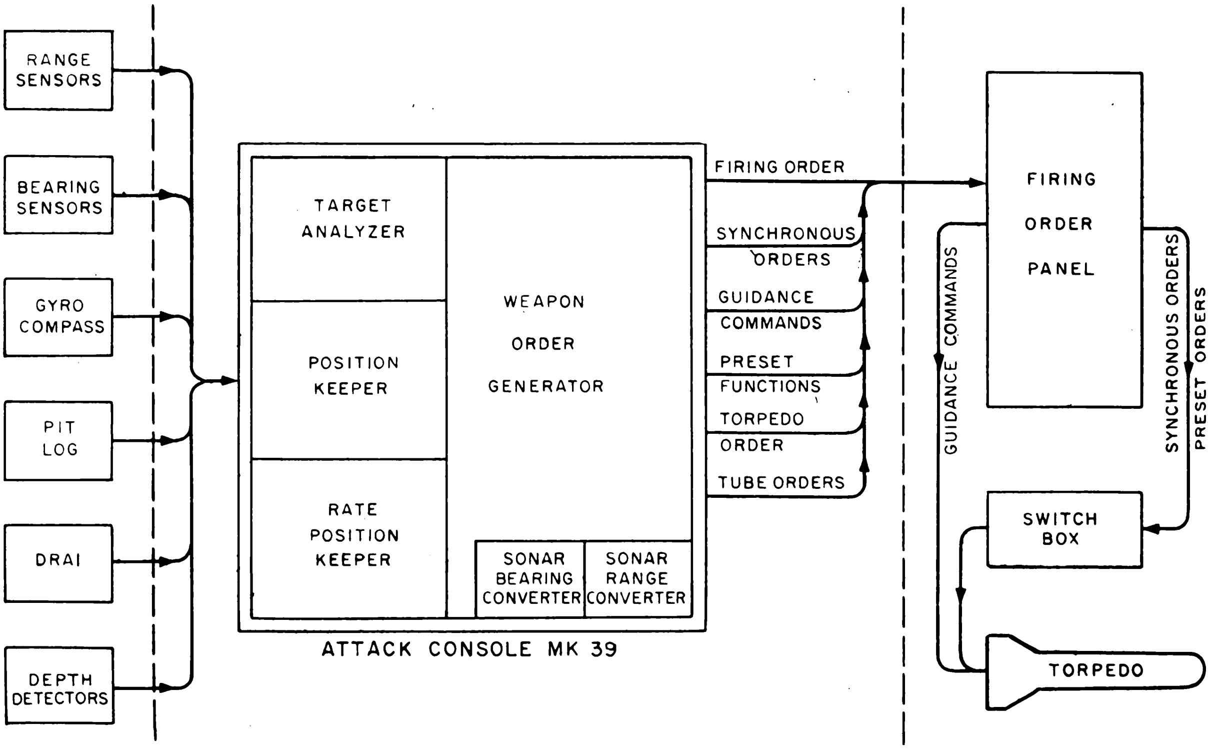

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Figure 15-22.—Submarine fire control system simplified block diagram.

the torpedo is actually accepting the synchronous inputs.

The FCS Mk 101 Mod 9 was the first attempt to integrate all functions of the fire control effort into a self-sufficient system. The addition of a target analyzer made possible the direct determination of target course and speed by the fire control system by using sensor and own ship data. The system also provided for the input of linear spread and the insertion of torpedo and tube orders.

CHAPTER 16

ADMINISTRATIVE DUTIES

It may seem strange that we have devoted an entire chapter to administration at the FT3 level. But as a member of the weapons department you are a partner in its administration. True, most of your working day is spent on a particular piece of equipment that is but a part of the entire fire control system. Therefore you probably think of yourself as being subjected to administration rather than being a part of it. Essentially, however, it is your work, ability, and training, plus your equipment, that is being administrated; and you have some say in the determination of administrative policies.

The operational and maintenance policies on your equipment are based in part on data obtained from the records and reports that you make. Thus administration is a tool to aid you, and is well worth the paperwork involved. The assistance you receive from administration is not always apparent; but the paperwork is, and in the name of expediency the paperwork is sometimes disregarded. When this happens everyone suffers, because something is taken away from the organization.

THE IMPORTANCE OF PAPERWORK

In any large business, records and reports are essential, and this is especially true of the Navy. In a worldwide operation involving ships of all sizes, with many types of equipment installed, and personnel constantly being transferred, the paperwork becomes even more important. If a man were assigned to and left with one type of equipment, or even on one ship for many years, he might feel that the paperwork in his daily routine is not important. But the administrative organization would need the reports and records on the equipment in order to know its operational status and to make a check on the troubles that occurred. Then replacement parts could be made available, alterations to improve the equipment made, training programs planned, and procedures of operation and maintenance would be quicker, safer, and more effective. The administrative organization starts within the FT gang and works its way up through the ship's weapons department to the captain, and from the ship through the channels within the fleet organization to the bureaus. For each operation, replacement, or maintenance step taken on the equipment there is paperwork involved, to hold the chain of information together.

As an illustration of the paperwork involved let's take a brief look at one component of a fire control system—a radar set. To begin with, we need a list identifying all the units in the radar set. The identification would include such information as the name of the unit, its type, mark and mod numbers, and serial number. Any alteration made to a unit, and any ordered alteration received but not performed, must be recorded with the unit's record. In this way we know exactly what the radar set consists of and what its designed capabilities are. Based on this information, performance, operation, and maintenance standards are established for the radar set. A record is kept of the operational performance and the results of the periodic test run on the radar. This information is compared with the standards to keep a running record of the operation of the radar. Any maintenance you perform must be recorded in detail. This information will indicate the reliability and maintainability of the radar, and show whether a change in the replacement parts carried by the ship or a modification to the radar set to eliminate a source of recurring trouble is necessary. If a defective part must be replaced you must initiate the paperwork necessary to obtain the replacement from the supply department. Finally, a record of the personnel assigned to operate and to maintain the radar, their qualifications, training program, and planned replacements must be kept.

This is but a rough sketch of the paperwork involved with one component in a system. It is sometimes difficult to associate the assistance you obtain from administration with the records and reports you make out in your daily routine.

Other than the military duties required of all petty officers, your professional duty as an FT3 will be largely that of keeping fire control in top working order. As part of your overall duty of maintaining fire control equipment, certain bookkeeping chores are involved. Some of these bookkeeping chores are part of your military duties and therefore are covered in Military Requirements for Petty Officer 3 & 2, NavPers 10056-B.

PUBLICATIONS

There are many publications used in the proper maintenance of fire control equipment. Technical publications issued by the various bureaus of the Department of the Navy are sources of important information for every man in the Navy. Publications by the Bureau of Naval Weapons, Bureau of Ships, Bureau of Supplies and Accounts, and the Bureau of Naval Personnel concern Fire Control Technicians. The most important publications from these sources that you should be familiar with are discussed in this chapter.

The Bureau of Naval Weapons has control of all publications formerly produced by the Bureau of Ordnance. Although the Bureau of Ordnance no longer exists, these publications will remain in effect until either rewritten or canceled by the Bureau of Naval Weapons. Thus, reference to Bureau of Ordnance publications should not be considered in error.

INSTRUCTIONS AND NOTICES

A system is in use throughout the Navy for the issuance of directive type releases, including those which prescribe policy, organization, methods, or procedures, and those which contain information. Certain publications, such as established manuals, operation releases, technical publications, some classified matter, and those joint Army-Navy-Air Force publications which are numbered serially, but do not have separate Army or Air Force designation are excluded from the system.

This program, called the Navy Directives System, provides a uniform plan for issuing and maintaining directives. Conformance to the system is required of all bureaus, offices, activities, and commands of the Navy. Two types of releases are authorized under the plan: Instructions and Notices.

INSTRUCTIONS are directives which contain information or require action of a continuing nature. An Instruction has permanent reference value and is effective until the originator supersedes or cancels it.

NOTICES are directives of a one-time nature and contain information or require action which can be completed immediately. A Notice does not have permanent reference value and contains provisions for its own cancellation.

For reasons of identification and accurate filing, all directives can be recognized by the originator's authorized abbreviation, the type of release (whether an Instruction or Notice) a subject classification number; and in the case of Instructions only, a consecutive number. Because of their temporary nature, the consecutive number is not assigned to Notices. This information is assigned by the originator and is placed on each page of the release.

The manner of numbering and identifying directives can be better understood by considering a typical identifier:

BuWeps	INST.	8260.1
(a)	(b)	(c) (d)

(a) Here the authorized abbreviation of the originator of the directive is placed.

(b) This part refers to the type of release, in this case an Instruction.

(c) This is the subject number which is determined by the subject matter of the directive, and is obtained from the Table of Subject Classification Numbers.

(d) Following the period is the consecutive number which is found only on Instructions. An originator would assign consecutive numbers to those consecutive instructions with the same subject classification number. In the example above, the Subject Classification Number 8260 concerns "Guided Missile Fire Control." If the originator, BuWeps, issued additional Instructions dealing with guided missile fire control, they would be assigned numbers 8260.2, 8260.3, 8260.4, etc. Subject classification numbers are listed in the Table of Subject Classification Numbers found in SECNAV Instruction

5215.1B. This table contains a numerical and alphabetical listing of numbers with their relates subjects, and is of considerable value for reference use when information or instructions of a particular nature are desired. This instruction contains all the necessary information for classifying documents by subject. The major numerical subject group, 8000-8999—Ordnance Material—is of interest to the Fire Control Technician.

A permanent file of instructions that are applicable to the ship is kept in the ship's office. This is the master file of instructions, specific or subject files are kept in the department offices. Thus a copy of all the ordnance instructions should be in the weapons office along with a copy of the Consolidated Subject Index (NavPubInst 5215.4B). Suppose we want to see if there are any instructions on the maintenance of a radar antenna. We would look in the index, which lists the instructions alphabetically by subject title. Under radar antennas we find that BuWeps Inst. 8222.1 applies to an antenna maintenance program. We would look at this instruction to see what the program consists of. The instructions are filed numerically.

NAVWEPS ORDNANCE PAMPHLETS

The primary source of technical information on operation, maintenance, adjustment, installation, and servicing of fire control and other ordnance equipment is the Ordnance Pamphlet (OP) series of publications. These are published by direction of the Bureau of Naval Weapons, each under its own OP number; but they may be prepared by some other naval activity, by a commercial specialist in such publications, or by the Bureau of Naval Weaspons itself. OPs are of two categories: equipment OPs and specific subject OPs.

EQUIPMENT OPs deal with the effective use of specific ordnance equipment. Each major unit of an ordnance installation is covered by an OP. Equipment OPs are organized according to the following general outline.

Introduction
Theory and functional description
How to operate the equipment
Physical description
Installation and assembly
Maintenance
Overhaul and repair
Appendixes
Index
Safety precautions

In the introduction you will find a brief explanation of what the equipment is, where it is used, what it is intended to do, and the like, as well as a description of the differences among various modifications, if appropriate.

Normally one chapter is devoted to each heading, though with complex equipment (like the Weapons Direction Equipment Mk 9) each topic may require an entire volume. Or, if the OP takes up a different assembly or subassembly in each chapter, the outline may be followed, so far as it is applicable, in the individual chapters. So there are variations, but the topic list above, or one much like it, is used by OP writers as their checklist; it shows what information you can expect to find in equipment OPs, and approximately where to find it. When you are working on fire control equipment make it a rule to have the applicable OP with you for ready reference.

SPECIFIC OPs take up a subject matter AREA rather than a specific item of ordnance equipment. Such OPs, of course, do not follow the standard outline above. But they are so written and indexed as to serve as a reference book for instruction and training. A good example of this type of OP is NavWeps OP 3000 (Volume I), Weapons Systems Fundamentals. This introduces and explains the fundamental principles of weapons and weapons system components.

ORDNANCE DATA

Ordnance Data (NavOrd ODs) contain routine test and inspection results. Installation and alignment data, parallax data, publications requirements lists, and ordnance equipment lists are normally provided in NavOrd ODs. Like the OPs, they are listed in the Index. Ordnance Data are often an important source of information for the maintenance man.

OD 9398, Fire Control Maintenance Notes, is published as a series of volumes. Each volume is concerned with a specific fire control system. These notes will be particularly helpful to you. They are available aboard ship. The information contained in these publications is kept up to date by frequent changes. A maintenance note will "point a finger" at a trouble which occurs commonly. It may be one that will occur to your equipment. Read these maintenance notes and be prepared. Refer to the notes if you encounter a particularly complex problem. Some other technician may have encountered this trouble, and if so, the solution is there for you.

INDEX OF ORDNANCE PUBLICATIONS

The Index of Ordnance Publications (Ordnance Pamphlet 0) is a listing of all types of ordnance publications stocked for issue by the Bureau of Naval Weapons.

The Index is divided into four parts. The first two parts list the publications numerically, the third part groups related publications by systems or installations, and the fourth part lists the publications alphabetically by their subject area. (The last revision of OP O changed it to this format.)

Part One of the index is divided into five sections. The first section consists of a numerical locator which indicates the status, (current; under preparation; obsolete) of all the OP numbers allotted. The locator also indicates in which section of the Index the description of an OP can be found. The second and third sections of part one contain numerical lists of current OPs; the lists are divided by the source from which the OPs are ordered. The numerical listings include: the OP number, the number of volumes and parts in the OP, the latest revision and last change made to the OP, the complete title, the date of publication, its security classification, and the desk (or group) in the bureau that has cognizance (responsibility for the content of the OP), over the publication. The fifth section contains a cross-reference between the NavWeps OPs and their related Illustrated Parts Breakdown (IPBs) manuals which are prepared by the Ordnance Supply Office (OSO).

Part Two of the Index deals with ODs in the same manner as part One handles OPs.

Part Three of OP consists of miscellaneous indexes of ordnance publications. The indexes included are: ordnance publications that cover a specific subject matter area, publications grouped by weapons systems or types of installation, a list of Department of the Army publications related by their subject area to Navy equipment, a list of ordnance charts, and a list of indexes other than the ones contained in this OP.

Part Four is called the Subject Index; it contains an alphabetical listing of the OPs and ODs by their subject area.

Use of OP O

OP O is normally kept in the weapons office. You usually know the name and identification data of the equipment rather than the number of a publication. Therefore, as an example we will start with the name of an equipment, the Target Designation System MK 5 Mod 1. The first step to finding the OPs or ODs on the system is to go to the Subject Index (Part Four), and look under the equipment's title "Target Designation Systems". Here you will find two OPs, 1964 and 2005, listed for the MK 5 Mod 1 system. The next step is to find these numbers in the OP Numerical Locator (Part One) and then go to the index indicated by the locator; in this example, the Cog 1 Index. The Index will give you the pertinent information on the OPs.

If you think there might be a NavOrd chart on the equipment, you would check the chart index (Part Three); charts are not listed in Part Four.

NEWSLETTERS

Newsletters are an important source of information, containing up-to-the-minute data on a particular weapons system. For example, the "3T" missile family—Talos, Terrier, and Tartar weapons systems each have a newsletter source of data. The newsletters serve the need for rapid dissemination of official BuWeps approved material, such as new or revised test procedures, troubleshooting techniques, methods of alignment and adjustment, and other technical information on a system. The information is obtained from fleet commands and units, shore activities, and industrial contractors. Later this information may be incorporated into the OPs and ODs on the system and may result in an alteration to the weapon system. The newsletters are distributed through the Bureau of Naval Weapons to all installations and activities concerned with the weapon system.

In weapon systems where changes are not quite so rapid or extensive, the Navy Directive System and OD9398, Fire Control Maintenance Notes, are used to keep you up to date on the system.

NAVWEPS FORMS

Forms are issued to provide the easiest, clearest, and most practical method of making reports and keeping records on the equipment.

A complete list of all the forms issued by the Navy is contained in NavSandA Publication 2002, the Navy Stock List of Forms and Publications, which are called cognizance I (cog I) items in the supply system. This publication is often referred to as the cog I manual and contains the information needed to order NavWeps forms. It also contains the drawing numbers for OPs, ODs, and other publications on the equipment. The list and the forms are continuously being revised and therefore it would not be practical to include here a list of forms applicable to fire control. The reports that must be submitted by your ship are listed in the type commander's Instruction (5213 series). This list is determined from the current revision of OPNAV Inst 5213.7 which is a consolidated listing of required reports. The type of forms which you will be dealing with in your daily routine will be covered later in this chapter.

ORDNANCE ALTERATIONS

Alterations to ordnance equipment approved by the Bureau of Naval Weapons are called ORDALTS. An OrdAlt instruction furnishes the necessary information to accomplish the ordalt, while an OrdAlt kit provides the material (hardware) needed for the alteration. A metal OrdAlt plate is attached to each major piece of ordnance equipment. The OrdAlt plate is normally mounted next to the unit's name plate. The number of a completed ordalt is stamped on the OrdAlt plate as a permanent record. The accomplishment of an ordalt is also recorded in the log book and in the machinery history of the equipment.

OrdAlts are numbered consecutively without regard to the applicability of equipment or vessel. OrdAlt 00 is an index of all the OrdAlts that have been issued and that are under preparation. The issued OrdAlts are listed numerically and by the applicable equipment.

Alterations which affect the military characteristics of a ship may be approved only by the Chief of Naval Operations and are called NAVALTS. If a NAVALT affects ordnance equipment, it is called a NAVALT ORDALT. Alterations to Bureau of Ships equipment are called SHIPALTS.

NAVAL WEAPONS BULLETINS

The Naval Weapons Bulletin is issued quarterly by the Bureau of Naval Weapons. The bulletin contains information on installed weapons systems and on systems and equipment in the development stage. The information ranges from detailed information on a particular system, to background information on present and future equipment.

CHANGES TO THE PUBLICATIONS

The Bureau is continuously reviewing its publications to keep them up to date. A vast amount of data on the operation, performance, testing, and maintenance of ordnance equipment is received and processed by the Bureau. When new methods are developed after a publication has been issued, a change to the publication is issued. The change may be a few words that can be made with a pen and ink; or an entire page or section of the publication may be changed, in which case substitute pages are contained in the change. Changes to a publication are numbered consecutively and should be made in that order. When the changes to a publication become too extensive, a revised edition is issued. The indexes of ordnance publications list the latest revision and the number of changes to each publication.

ACCEPTANCE DATA

The ship's acceptance tests which were run when the equipment was installed, together with the factory acceptance test, constitute a criterion for evaluating subsequent tests and performance of the equipment. The ship's acceptance test results should be copied in the logbook of the equipment or system so as to be available for convenient future reference. This has been done for us in the equipment covered by a maintenance program. (We will discuss the program later.)

BUREAU OF SHIPS PUBLICATIONS

The Bureau of Ships is responsible for shipboard equipment—often thought of as ordnance equipment, such as ammunition dredger hoists, some fire control switchboards, and director or mount foundations. Thus there are BuShip's publications (called NavShips publications), of interest to the FT. We will mention two NavShips publications that contain information used by the FT.

Bureau of Ships Technical Manual

Bureau of Ships Technical Manual, NavShips 250-000, contains data and instructions pertaining to classes of installed machinery and equipment. The data is in accordance with what is considered the best engineering practices for the operation, maintenance, testing, and safety of the equipment. Since the information deals with classes of equipments, it is general information and can provide you with background information that is supplementary to the data contained in the equipment's OP or OD.

The chapters in the "Tech Manual" on electrical and electronic equipment and installations will be of particular interest to you. These chapters were in the 60 series in the book's former numbering system. In the newer system the chapters are in the 9600 series. The numbering system was changed to conform with the Navy-Marine Corps Standard Subject Classification System. Chapter 9710 (formerly 71) titled Fire Control Installations is of prime interest to you.

Electronics Installation and Maintenance Books

The Electronics Installation and Maintenance Books, NavShips 900,000 series, are published by the Bureau of Ships to provide subordinate policies, and installation and maintenance information standards for naval electronic equipment. The series is intended to reduce time-consuming research on electronic equipment and circuit theory, and contains a great deal of information of interest to the FT. The series is divided into several volumes, each volume can be ordered as an individual item.

CLASSIFIED PUBLICATIONS

Many fire control publications are classified. Most of this material is in the confidential category. The security measures required in the handling of classified material are covered in OPNAVINST 5510.1B, titled Department of the Navy Security Manual for Classified Information. Generally, the responsibility for handling classified matter involves the receipt, accounting for, making changes to, and distribution of all such matter. Everyone who has access to classified material must be familiar with the information in the "Security Manual".

SHIP'S PLAN INDEX

The plans and diagrams of the fire control equipment are the road maps of maintenance. Generally speaking, there are two basic sources of this type of information—the Ship's Plan Index and the Bureau of Weapons ordnance drawings. The Ship's Plan Index (S.P.I.) is prepared by the shipbuilding yard and is normally maintained aboard ship by the Engineering Office. The S.P.I. lists the wiring diagrams of fire control circuits, and the general arrangement and installation plans of the fire control equipment for your ship. The list does not include diagrams of the equipment's internal arrangements and electrical circuits. The Bureau of Naval Weapon's publications of ordnance drawings deals with the internal diagrams.

ORDNANCE DRAWINGS

A master list of drawings is prepared for each major piece of ordnance equipment. This list includes all components of the equipment. Each component is itemized by assemblies, subassemblies, and details on a separate list of drawings (LD).

The identifying number for each component LD is given, together with the general arrangement drawing number, on the master list of drawings for the equipment. Each component list of drawings also shows the special tools required for servicing that component. By reference to the list of drawings and the drawings for the mark and mode of a given assembly or subassembly, it is possible to work down to an individual part and to identify the correct nomenclature, drawing, piece number, design dimensions, tolerances, and all other necessary information.

How to read and interpret wiring diagrams and drawings is covered in the basic course, Blueprint Reading and Sketching, NavPers 10077-B.

ORDNANCE MATERIAL MAINTENANCE REPORTS AND RECORDS

The purpose of all ordnance material maintenance reports and records is to aid in the upkeep, repair, and improvement of ordnance materials (fire control radars, guns, missile and rocket launchers, directors, computers, etc.).

REPORTS

Reports are a means of transmitting information concerning the upkeep, repair, and improvement of ordnance equipment to technical sections in the Bureau of Naval Weapons and to other interested activities.

Many FTs feel that making out reports serves no useful purpose. Nothing could be further from the truth. Actually, reports to BuWeps and to type commanders are the basis for the alteration and improvement of fire control and other ordnance equipment. For example, if 50 destroyers submit failure reports of a similar nature on a servomotor, it is likely that BuWeps will issue an Ordnance Alteration (OrdAlt) for that type of servomotor to improve its design, or make changes to the circuit in which the motor is used to eliminate the cause of failure. Without reports there would be no basis for improving the motors.

Component Failure Report

One of the reports that you will most frequently fill out is the Weapon Systems Component Failure Report NAVWEPS.FORM 8000/13, (fig. 16-1). This report provides the Bureau with concise information on the failures and malfunctions of nonexpendable units in the weapon system. Complete information on the failure report can be found in NAVWEPS INST. 8000.3. This form supersedes both the Electronic Failure Report (DD 787) and the Equipment Casualty Report (NAVORD FORM 2214).

This report is normally prepared by the FT who actually locates the trouble or repairs the equipment. Reports should be signed by the technician effecting the repairs or diagnosing the failure. Review by the division officer or a designated chief or other petty officer is optional with the reporting activity. Reports may be completed by using pencil, pen, or typewriter; but they must be legible.

The importance of reporting failures and their causes cannot be too highly stressed. You can be sure that your efforts in filling out the failure report will be put to good use.

The technician on the spot of the trouble is in the best position to prepare data to keep the engineers and manufacturers informed as to whether equipment works properly. He is a vital link between the fleet and the bureaus in the feedback of failure data. Bureau engineers have a high regard for the shipboard technician. They know the difficult situation in which the technician often finds himself: he is required to get an equipment working within a certain time; he may or may not have the best training, the test equipment, and the maintenance parts to fix it. But fix it he must—and does.

Operability and Reliability Reports

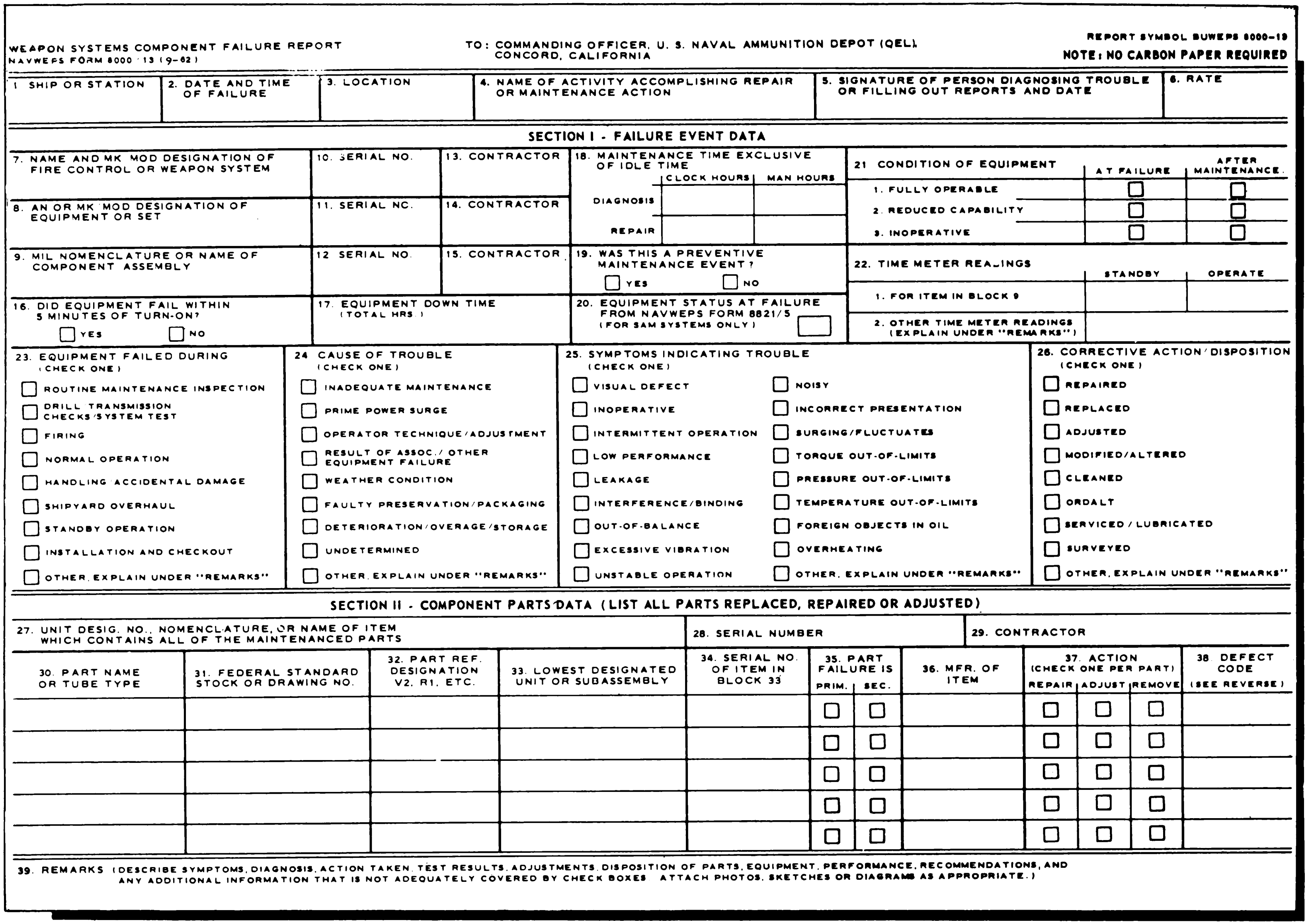
The Daily System Operability Tests (DSOT) provide systematic, unambiguous, quickly performed test procedures for determining the readiness of the weapons system. The results of the tests are recorded on NAVWEPS Form 8821/5 (fig. 16-2). Equipment Status Report, which is submitted weekly to the addresses listed in the latest change to BUWEPSINST 8821.3. Code letters are used to indicate the condition of the weapons system, with space for recording each hour of the day. The code letters are explained in enclosure (1) of BUWEPS-INST 8821.3A. Whenever the system is down for any reason, the explanation should be given under "Remarks". In the example shown in figure 16-2 the system could not be operated because of failure of support equipment (code P); the name of the failed equipment and the type of failure are written into the Remarks column. Each ship is notified on which equipments it is to report and a Form 8821/5 is submitted each week for each such equipment.

Maintenance Records

Maintenance records are kept to show a continuous history of the performance and required maintenance of either a type or a particular piece of ordnance equipment. The three basic continuing records kept in the weapons department are the Ordnance History, the Current Ship's Maintenance Project, and Ordnance Logs. When kept up to date these records provide a valuable reference, aid in maintenance and repair work, and improve the quality and performance of the equipment. The value of these records as references depends upon the accuracy of the entries made in them. You will, in many instances, be responsible for supplying the correct information to be entered in the logs, Ordnance History, and CSMPs.

Ordnance Logs

The log for any particular piece of equipment or system is a day-to-day history in which all information of importance is recorded. It contains information concerning test, overhaul, repair, alteration, and maintenance. Ordnance logs may be kept in longhand or they may be



WEAPON SYSTEMS COMPONENT FAILURE REPORT
NAVWEPS FORM 8000/13 (9-62)

TO: COMMANDING OFFICER, U. S. NAVAL AMMUNITION DEPOT (QEL),
CONCORD, CALIFORNIA

REPORT SYMBOL BUWEPS 8000-19
NOTE: NO CARBON PAPER REQUIRED

1. SHIP OR STATION
2. DATE AND TIME OF FAILURE
3. LOCATION
4. NAME OF ACTIVITY ACCOMPLISHING REPAIR OR MAINTENANCE ACTION
5. SIGNATURE OF PERSON DIAGNOSING TROUBLE OR FILLING OUT REPORTS AND DATE
6. RATE

SECTION I - FAILURE EVENT DATA

7. NAME AND MK MOD DESIGNATION OF FIRE CONTROL OR WEAPON SYSTEM
8. AN OR MK MOD DESIGNATION OF EQUIPMENT OR SET
9. MIL NOMENCLATURE OR NAME OF COMPONENT ASSEMBLY
10. SERIAL NO.
11. SERIAL NO.
12. SERIAL NO.
13. CONTRACTOR
14. CONTRACTOR
15. CONTRACTOR

18. MAINTENANCE TIME EXCLUSIVE OF IDLE TIME

	CLOCK HOURS	MAN HOURS
DIAGNOSIS		
REPAIR		

19. WAS THIS A PREVENTIVE MAINTENANCE EVENT? ☐ YES ☐ NO

21. CONDITION OF EQUIPMENT

	AT FAILURE	AFTER MAINTENANCE
1. FULLY OPERABLE	☐	☐
2. REDUCED CAPABILITY	☐	☐
3. INOPERATIVE	☐	☐

22. TIME METER READINGS

	STANDBY	OPERATE
1. FOR ITEM IN BLOCK 9		
2. OTHER TIME METER READINGS (EXPLAIN UNDER "REMARKS")		

16. DID EQUIPMENT FAIL WITHIN 5 MINUTES OF TURN-ON? ☐ YES ☐ NO
17. EQUIPMENT DOWN TIME (TOTAL HRS.)
20. EQUIPMENT STATUS AT FAILURE FROM NAVWEPS FORM 8821/5 (FOR SAM SYSTEMS ONLY) ☐

23. EQUIPMENT FAILED DURING (CHECK ONE)
- ☐ ROUTINE MAINTENANCE INSPECTION
- ☐ DRILL, TRANSMISSION CHECKS/SYSTEM TEST
- ☐ FIRING
- ☐ NORMAL OPERATION
- ☐ HANDLING ACCIDENTAL DAMAGE
- ☐ SHIPYARD OVERHAUL
- ☐ STANDBY OPERATION
- ☐ INSTALLATION AND CHECKOUT
- ☐ OTHER, EXPLAIN UNDER "REMARKS"

24. CAUSE OF TROUBLE (CHECK ONE)
- ☐ INADEQUATE MAINTENANCE
- ☐ PRIME POWER SURGE
- ☐ OPERATOR TECHNIQUE/ADJUSTMENT
- ☐ RESULT OF ASSOC./OTHER EQUIPMENT FAILURE
- ☐ WEATHER CONDITION
- ☐ FAULTY PRESERVATION/PACKAGING
- ☐ DETERIORATION/OVERAGE/STORAGE
- ☐ UNDETERMINED
- ☐ OTHER, EXPLAIN UNDER "REMARKS"

25. SYMPTOMS INDICATING TROUBLE (CHECK ONE)
- ☐ VISUAL DEFECT
- ☐ INOPERATIVE
- ☐ INTERMITTENT OPERATION
- ☐ LOW PERFORMANCE
- ☐ LEAKAGE
- ☐ INTERFERENCE/BINDING
- ☐ OUT-OF-BALANCE
- ☐ EXCESSIVE VIBRATION
- ☐ UNSTABLE OPERATION
- ☐ NOISY
- ☐ INCORRECT PRESENTATION
- ☐ SURGING/FLUCTUATES
- ☐ TORQUE OUT-OF-LIMITS
- ☐ PRESSURE OUT-OF-LIMITS
- ☐ TEMPERATURE OUT-OF-LIMITS
- ☐ FOREIGN OBJECTS IN OIL
- ☐ OVERHEATING
- ☐ OTHER, EXPLAIN UNDER "REMARKS"

26. CORRECTIVE ACTION/DISPOSITION (CHECK ONE)
- ☐ REPAIRED
- ☐ REPLACED
- ☐ ADJUSTED
- ☐ MODIFIED/ALTERED
- ☐ CLEANED
- ☐ ORDALT
- ☐ SERVICED/LUBRICATED
- ☐ SURVEYED
- ☐ OTHER, EXPLAIN UNDER "REMARKS"

SECTION II - COMPONENT PARTS DATA (LIST ALL PARTS REPLACED, REPAIRED OR ADJUSTED)

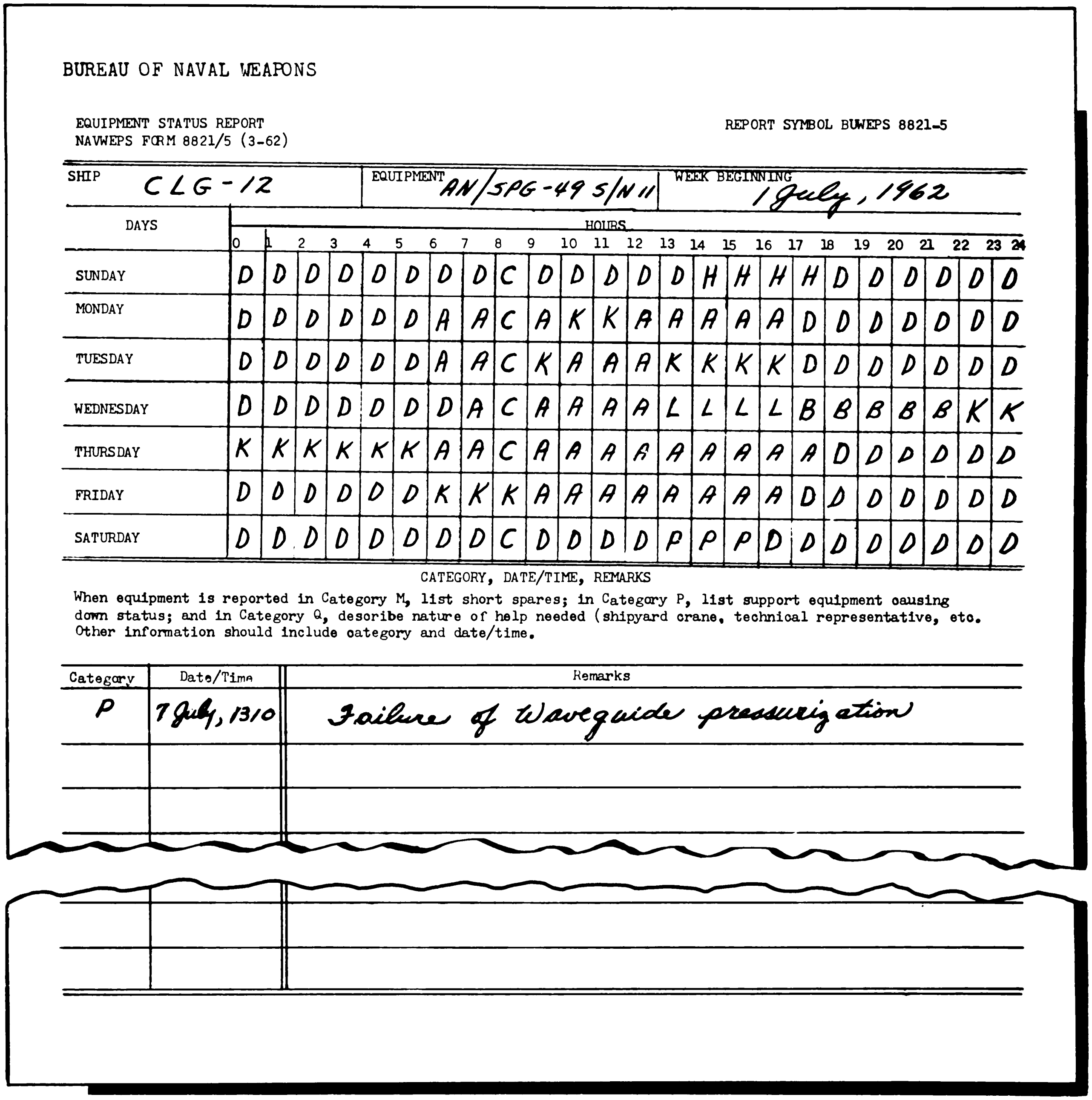
27. UNIT DESIG. NO., NOMENCLATURE, OR NAME OF ITEM WHICH CONTAINS ALL OF THE MAINTENANCED PARTS
28. SERIAL NUMBER
29. CONTRACTOR

30. PART NAME OR TUBE TYPE	31. FEDERAL STANDARD STOCK OR DRAWING NO.	32. PART REF. DESIGNATION V2, R1, ETC.	33. LOWEST DESIGNATED UNIT OR SUBASSEMBLY	34. SERIAL NO. OF ITEM IN BLOCK 33	35. PART FAILURE IS		36. MFR. OF ITEM	37. ACTION (CHECK ONE PER PART)			38. DEFECT CODE (SEE REVERSE)
					PRIM.	SEC.		REPAIR	ADJUST	REMOVE	
					☐	☐		☐	☐	☐	
					☐	☐		☐	☐	☐	
					☐	☐		☐	☐	☐	
					☐	☐		☐	☐	☐	
					☐	☐		☐	☐	☐	

39. REMARKS (DESCRIBE SYMPTOMS, DIAGNOSIS, ACTION TAKEN, TEST RESULTS, ADJUSTMENTS, DISPOSITION OF PARTS, EQUIPMENT, PERFORMANCE, RECOMMENDATIONS, AND ANY ADDITIONAL INFORMATION THAT IS NOT ADEQUATELY COVERED BY CHECK BOXES. ATTACH PHOTOS, SKETCHES OR DIAGRAMS AS APPROPRIATE.)

92.101

Figure 16-1.—Weapon Systems Component Failure Report, NavWeps Form 8000/13.



BUREAU OF NAVAL WEAPONS

EQUIPMENT STATUS REPORT
NAVWEPS FORM 8821/5 (3-62)

REPORT SYMBOL BUWEPS 8821-5

SHIP CLG-12
EQUIPMENT AN/SPG-49 S/N 11
WEEK BEGINNING 1 July, 1962

DAYS	HOURS 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23 24
SUNDAY	D	D	D	D	D	D	D	D	C	D	D	D	D	D	H	H	H	H	D	D	D	D	D	D
MONDAY	D	D	D	D	D	D	A	A	C	A	K	K	A	A	A	A	A	D	D	D	D	D	D	D
TUESDAY	D	D	D	D	D	D	A	A	C	K	A	A	A	K	K	K	K	D	D	D	D	D	D	D
WEDNESDAY	D	D	D	D	D	D	D	A	C	A	A	A	A	L	L	L	L	B	B	B	B	B	K	K
THURSDAY	K	K	K	K	K	K	A	A	C	A	A	A	A	A	A	A	A	A	D	D	D	D	D	D
FRIDAY	D	D	D	D	D	D	K	K	K	A	A	A	A	A	A	A	A	D	D	D	D	D	D	D
SATURDAY	D	D	D	D	D	D	D	D	C	D	D	D	D	P	P	P	D	D	D	D	D	D	D	D

CATEGORY, DATE/TIME, REMARKS

When equipment is reported in Category M, list short spares; in Category P, list support equipment causing down status; and in Category Q, describe nature of help needed (shipyard crane, technical representative, etc. Other information should include category and date/time.

Category	Date/Time	Remarks
P	7 July, 1310	Failure of Waveguide pressurization

33.242

Figure 16-2.—Equipment Status Report, NavWeps 8821/5.

typed. The Bureau considers that a legible handwritten log serves every purpose for which a log is needed.

Printed logs consisting of forms in which data and information are entered are issued by the Bureau for some equipments. Computer Mk 1A Log Book, NavOrd Form 1229, is a typical example. These logs are issued as Nav Weps Forms and are automatically furnished to ships having the applicable equipment.

The true value of a log can be realized only if entries are made promptly and accurately. As an FT3 you may be given the responsibility of keeping a log. Periodic review of log books permits analysis of casualties, aids in discovering design deficiencies brought to light by recurring faults, and enables detection of faulty maintenance.

Among the various classes of logs, two of the major classifications are: Battery Logs and Fire Control Logs. As a minimum requirement, Fire Control Logs are to be maintained for the fire control equipment aboard ship as follows:

a. Fire Control System	1 per system
b. Computer and/or Rangekeeper	1 per computer and/or rangekeeper
c. Stable Element	1 per stable element
d. Target Designation Equipment	1 per system
e. Fire Control Radar	1 per equipment
f. Gun Sight Log	1 per ship
g. Rangefinder and Optical	1 per ship
h. Battery Alignment	1 per battery

Ballistic Log

The ballistic log should be maintained to show the gun ballistic variables. One should be kept for each gun battery. In this log are kept the rounds fired by each gun, star gauge data and bore erosion gauge data. This information should be recorded for each gun by serial number of the barrel. It forms the basis for computation of Equivalent Service Rounds (ESR) which is a factor in computing Initial Velocity (IV.). In it can be recorded any data affecting the ballistic of any particular gun or battery. The ballistic logs are usually kept by the Fire Control Officer or Senior Fire Control Technician.

Since the logs are intended to be a daily history of important events concerning the equipment, care should be exercised in making entries. Data should be recorded in tabular form insofar as it is practicable. Typical items for entry into these logs are listed below.

Items applicable to both Battery Logs and Fire Control Logs are:

1. List of major units or subassemblies including mark, mod, serial number. (This list should be in the first pages of the log and is intended to aid the logkeeper in proper identification of units of equipment.)
2. Drills and exercises involving equipment.
3. The execution of routine prefiring and postfiring checkoff lists.
4. Any use of lubricants different from those specified, and reasons therefor.
5. Record of tests, checks, and measurements, including megger readings.
6. Resume of maintenance not covered by checkoff lists, such as: filing, flushing, or draining of hydraulic units; lifting of equipment for inspection; boresighting and star gauging.
7. Adverse effects of weather on material maintenance or operation.
8. Record of special inspections.
9. Detailed description of casualties giving name, mark, mod, serial number, and part number of unit and parts involved, what happened, probable cause, how repaired, and steps taken to prevent recurrence.
10. Resume of repairs made, including complete identification of part or parts affected, parts replaced, and probable cause.
11. Brief resume including number of any pertinent OrdAlt, ShipAlt, Field Change, or Bureau authorized modification performed.
12. Report of hit or damage to equipment from outside source.
13. Record of tram readings, roller path compensator readings, and erosion indicator readings.

Items peculiar to Fire Control Logs are:

1. Alignment data, including errors discovered and how corrected, and targets used.
2. Hours of operation of fire control radar, computers, and stable elements, in tabular form.
3. Cleaning details of optical maintenance.
4. Drydock alignment data.
5. Daily test of cease firing gongs, buzzers, and lights.

Routine items concerning cleaning, ship's drills, or other events not concerning the equipment should be omitted. On days when no items of interest occur, the date and initials of the logkeeper are listed.

Ordnance History

The weapons officer is responsible for keeping the Ordnance History complete and up to date. But, as mentioned previously, some share of the work will be in your hands; therefore, you should know the purpose of this record, and how it is kept.

The Ordnance History is a complete record of maintenance, repair, and alterations on ordnance equipment. It is a compilation in a card file of past equipment operation (including casualties) and present condition. These cards are made up from entries made in logs. Every piece of ordnance equipment on board ship is included in the history.

The Ordnance History maintained on the following cards:

1. NavOrd Form 2032—Ordnance History Card
2. NavShips Form 527—Machinery History Card (Electrical)
3. NavShips Form 531—Resistance Test Record
4. NavShips Form 536—Electrical Equipment History Card
5. NavShips Form 532—Blank Utility Card

A MacMillan looseleaf binder is recommended for holding these cards. When cards are removed from the binder, care must be taken to ensure that they are not lost, or replaced in incorrect order.

Current Ship's Maintenance Project

The Current Ship's Maintenance Project (CSMP) comprises a very important record, one that is referred to frequently by your division officer, weapons officer, and chief. It shows what has to be done with respect to alterations and repairs to equipment, as well as what has been done. It must be complete and up to date. The two standard forms used in its make-up are NavOrd Form 2033 (Repair Card), and NavOrd Form 2034 (Alteration Card). These cards form the CSMP file. In general, you can think of the CSMP file as being a record of future alterations and repairs. It usually lists jobs that are to be done when the ship is alongside a tender or repair ship, or at a naval shipyard. This does not necessarily mean that each job listed in the CSMP is beyond the capabilities of the ship's force (though some of them may be); it includes all repairs and alterations to be accomplished, whether by ship's force or other repair personnel. You should note, by the way, that the CSMP in no way supplants the Ordnance History. The CSMP applies only to equipment requiring repair or alteration, while the Ordnance History applies to ALL ordnance equipment.

ORDNANCE SUPPLY

This section outlines your functions with regard to the supply department and with the ordering of repair parts, equipage, and consumable materials. It tells you, in a general way, what you have to know in order to draw repair parts or other materials.

COSAL AND WHAT IT MEANS

The Coordinated Shipboard Allowance List (COSAL) was explained and illustrated in Military Requirements for Petty Officer 3 & 2, NavPers 10056-B. As an FT the part of the COSAL that concerns your work is the ordnance section that lists the fire control systems and the tools and repair parts allowed for their maintenance. The ordnance section of the COSAL is made up of an introduction and three separate parts. The introduction gives complete information on the use of the COSAL.

The format of the ordnance segment of the COSAL conforms to the segment illustrated in the military requirements training course mentioned before. The procedures for preparing requisitions to order materials was also explained in that training course. Therefore we will proceed on to the subject of establishing the identification of ordnance materials. This will be your main job in ordering ordnance material.

SOURCES OF ORDNANCE IDENTIFICATION

The publications most often used to identify ordnance material are:

1. Navy Stock List of the Ordnance Supply Office (NSL of OSO). The first three volumes are the ones you will use most for identifying repair parts for requisitioning.

2. Illustrated Parts Breakdown of Ordnance Equipment (IPB). This publication is prepared by OSO. Each IPB is published for one particular type of piece of equipment, and describes and illustrates the relationship of all assemblies and parts comprising the equipment. IPB 0000 is an index of all IPBs.

3. Coordinated Shipboard Allowance List (COSAL), which were previously discussed.

One of the most important sources of identification is the information on nameplates. This may include the manufacturer's name, make or model number, size, voltage, and like information. Identification publications such as manufacturers' technical manuals may help you in identifying an item.

ORDNANCE IDENTIFICATION DATA

Ordnance identification data are important in identifying ordnance items. They should be used on all requests for material if the stock number is not available. These data include:

The MARK NUMBER, which identifies the particular model of a certain type of ordnance equipment.

A MODIFICATION NUMBER (Mod), which indicates a modification of the basic mark number. Modifications are numbered serially, beginning with zero, for each separate mark.

An IDENTIFYING NUMBER, which is the number assigned to the blueprint plan of an ordnance component or assembly. It may be a drawing number, a list of drawing numbers (LD), a sketch number, or an assembly number.

A PIECE NUMBER, which is a subdivision of the drawing number and identifies by a serial designation every item appearing on a given drawing. Sometimes the drawing and piece numbers are stamped or etched onto the part itself. Piece numbers are rarely used in later type ordnance assembly drawings. It is now standard practice that each item in a drawing will have its own separate drawing number.

A revision letter is often added to identify a particular revision of a drawing or list of drawings used in the manufacture of a part.

MAINTENANCE SYSTEMS

The complexity of the fire control equipment intensifies an already serious maintenance problem. Efforts are continually being made to "build in" maintainability and reliability into the equipment to reduce the need for shipboard maintenance. But maintenance remains one of the major factors in sustaining the equipment in a state of operational readiness. To meet the maintenance challenge of the equipment and the new situations you may experience, specific information on the equipment is necessary. To train all the men on all the equipment, however, is not practical.

The FT has been well trained in basic theory and skills, therefore the maintenance problem is not "how to do it" but "what to do." Thus the key to the maintenance problem is up-to-date maintenance oriented information on the specific piece of equipment—in other words, increased maintenance know-how on the equipment. One of the primary purposes of the Navy maintenance systems is to provide this maintenance know-how, by sharing the knowledge and experience gained on the equipment throughout the Navy. Hence, you will not be "on your own" when performing maintenance, because the combined knowledge of the fleet, the bureaus, and the manufacturer is at your finger-tips.

The Navy maintenance systems have been tailored to meet the needs of the equipment. Let's briefly discuss the maintenance systems in their evolutionary order. The first such system was called POMSEE and dealt only with electronic equipment (in fire control, mainly the radar sets). The word POMSEE stands for "Performance, Operation, and Maintenance Standards for Electronic Equipments". The radar is an integral part of some fire control systems and it is difficult to separate the radar's operation from that of its associated equipment.

The Satterwhite system was developed aboard ship by Chief Fire Control Technician Charles E. Satterwhite. This was a complete maintenance system for the Gun Fire Control System Mk 56. The maintenance system had a consolidated list of all the maintenance jobs arranged in a systematic schedule. Each job was described on a Job Description Card (JDC). The job was broken down into simple easy to follow steps; the tools, materials, test equipment, and references needed to do the job were listed. Illustrations were provided when there was a need to locate or to clarify a point in the job description. Little had been left to chance.

The PRISM system, "Programmed Integrated System Maintenance," was to be designed for all gun fire control systems. PRISM was a logical evolution of the Satterwhite System and incorporated many of its features. But some fire control systems, particularly the missile systems, are an integral part of a weapon system, and its maintenance requirements are closely integrated with the entire system.

The Integrated Maintenance Plan (IMP) was devised to provide a maintenance program for an entire weapon system instead of the individual equipment within the system. IMP contains a complete schedule of all the maintenance events for the system. The schedule is arranged to ensure efficient use of the men involved and a comprehensive testing and servicing of the equipment. Since IMP includes the whole weapon system, close coordination between the rating associated with the system is necessary.

The Daily System Operability Tests (DSOT), and other test procedures (to be performed at less than daily frequencies), comprise the testing portion of IMP. The testing portion is tied or keyed to associated system troubleshooting aids. These aids consist of Logic Trees, for isolating faulty equipment of the system, and Pyramids, for isolating faults within an equipment of the system. Logic trees and pyramids will be covered under troubleshooting in the next chapter.

IMP was devised by BuWeps to provide a maintenance program for a weapon system. The next obvious step is to expand the maintenance system to include the entire ship. Each ship type is considered as a complete system and all plannable maintenance is scheduled in a single integrated maintenance program.

NAVY MAINTENANCE AND MATERIAL MANAGEMENT SYSTEM

The Navy Maintenance and Material Management System, called the 3-M system, is a uniform plan of maintenance with an internal central management aboard ship to coordinate a shipwide maintenance system and an external central management to coordinate the maintenance system and maintenance data collection Navy-wide. The 3-M system was developed by the office of the CNO to coordinate the work of BuWeps, BuShips, and BuSandA with respect to equipment maintenance. To accomplish this extensive program the 3-M system embraces two broad areas: the Planned Maintenance System and the Maintenance Data Collection System.

The organization and administration of the 3-M system are covered in Military Requirements for P.O. 3 & 2, NavPers 10056-B. Study this material thoroughly, for the 3-M system will be used exclusively throughout the Navy.

The Planned Maintenance System (PMS) supersedes all other maintenance systems such as POMSEE, Satterwhite, PRIMS, and IMP. Perhaps we should have used the word "absorbed" rather than "supersede" because most of the management tools and maintenance techniques of the former systems have been incorporated into the PMS. Thus it will not be difficult for you to become accustomed to working with the PMS.

Each piece of equipment was studied to determine the amount of servicing required to sustain its operational performance and the tests required to check its performance. The study was made on the piece of equipment as an individual item and as it functions as part of a complete system. The maintenance orientated data was processed and integrated into the PMS. The PMS contains the minimum amount of plannable maintenance necessary to keep the equipment and the system in a state of operational readiness. Each command however, retains the prerogative to increase the maintenance to meet local conditions.

The tests which include the daily system operability tests and the tests for each piece of equipment are run on a prescribed schedule. The maintenance requirements of the system and the equipment are broken down into simple tasks that are described on the Maintenance Requirement Cards (MRC), in an easy to understand step-by-step procedure. The MRC and maintenance scheduling are covered in Military Requirements for Petty Officer 3 & 2, NavPers 10056-B and therefore will not be discussed here.

Some of the MRCs on fire control equipment are classified. The classified MRCs are stored separately and have a different color than the unclassified MRCs (classified MRCs are normally pink). The classified maintenance tasks are scheduled on the same schedule as the unclassified tasks.

It should be brought out that general safety precautions are not listed on MRCs; only specific precautions that are related to the maintenance task are listed. Keep this fact uppermost in your thoughts while on the job. We will discuss general safety precautions pertinent to fire control equipment in the next chapter of this course.

Moreover, only unique operating situations dealing with the task are contained on the MRC. It is assumed that you are familiar with the normal operation of the system or equipment. Thus a basic requirement of the PMC is to know the operation of your equipment.

SHIPBOARD MAINTENANCE DATA COLLECTION SYSTEM

The primary purpose of the Maintenance Data Collection System (MDCS), is to ensure that the basic maintenance data is recorded once, and only once, and that the system provides the information to all who need it. Data in the MDCS flows in three distinct but related cycles: (1) local cycle; (2) local-central cycle; (3) central-external cycle.

The local cycle—the basic source of data—is the maintenanceman aboard ship who provides information to the local central. After keypunching the source data onto standard Electric Accounting Machine (EAM) cards, the punched cards are forwarded daily or at other specified time intervals to the central data processing activity, where they are recorded on computer tapes for computer processing. Navy-wide data, as applicable and appropriate, is then sent back to the reporting units. This completes the cycle—the technician now has maintenance data with which he can improve his operations; he can also compare his actions and equipment with those of the rest of the fleet.

The central-external cycle, in addition to supplying "feedback" data to the reporting units, also supplies the data to the appropriate Bureau. At the Bureau the maintenance data is evaluated to determine if either the equipment or the maintenance procedures can be improved.

The shipboard maintenance reports and records required by the MDCS are all made on the OPNAV forms 4700-2 series. The use of the 4700-2 series of forms is covered in your military requirements course. The MDCS provides a uniform means to record maintenance actions aboard ship. This in itself has simplified your paperwork connected with maintenance, but at the same time the data contained and retained in the data system has become more complete. Many of the various reports and records formerly used were replaced or eliminated by the MDCS. Former records and reports such as the CSMP and the BuWeps form 8000/13 were included in this chapter to ensure the completeness of coverage for all types of ships. The shipboard portion of the MDCS provides a guide for the administration of maintenance data, but local conditions as determined by the fleet or type command may require the use of some of the former records and reports.

CHAPTER 17

MAINTENANCE AND TROUBLESHOOTING

The effectiveness of your equipment depends largely upon the care and attention you give it. An improperly adjusted computer, for example, can reduce the accuracy of a perfectly aligned battery.

The work you perform on equipment falls into two broad categories: (1) actions you take to reduce or eliminate failure and prolong the useful life of your equipment, and (2) actions you take when a part or component has failed and the equipment is out of service. Therefore, we can think of the whole business of general maintenance as consisting of PREVENTIVE maintenance and CORRECTIVE maintenance.

In maintenance work of any type, you must use knowledge and skills of two fundamental kinds. First, you must have SPECIFIC information which applies only to the particular equipment which you may be called upon to repair or keep in good condition. Secondly, you must possess and use certain GENERAL skills and knowledge which apply to many kinds of equipment and to many types of work assignments.

The specific information required consists of special procedures and processes, and detailed step-by-step directions used to maintain a particular piece of equipment. This information is supplied in the 3M maintenance system and in publications by BuWeps, fleet, or type commanders.

The general maintenance skills and procedures are based on knowledge which is not contained in equipment OPs but must be learned on the job and from Navy Training Courses. This information forms the basic content of this chapter.

PREVENTIVE MAINTENANCE

We have indicated in the preceding discussion that one of the two maintenance categories is preventive maintenance. What is preventive maintenance? Let's use a familiar experience to illustrate the meaning of the term. You have probably owned a car or in some way have had a share of the responsibility of car ownership. Undoubtedly you found out that there is more to owning a car than simply driving it. Air pressure in the tires, oil, and water have to be checked. The car has to be washed and waxed to prevent deterioration. Periodically, the brakes must be adjusted, the sparkplugs cleaned, and the motor given a tuneup by adjusting the ignition system. If you faithfully follow this preventive maintenance routine, it is unlikely that your car will be laid up for long repair periods.

The same line of reasoning applies if you have a lot of down-time for the repair of fire control equipment. In many instances, the failure of the part or component that caused the equipment malfunction or casualty can be traced to improper preventive maintenance.

The procedures for maintaining fire control equipment are not exactly those you follow in taking care of a car, but the purpose is identical. The sole purpose of preventive maintenance is to stop trouble before it starts.

THE FOUR-POINT PROGRAM

Preventive maintenance, then, consists of the care, upkeep, and minor repairs and adjustments performed by the technician to ensure the best condition of his equipment and to reduce the chance of sudden equipment failure or malfunction. It involves four major types of activity:

1. periodic cleaning
2. periodic lubrication
3. periodic inspection
4. periodic performance checks

In some of the following sections of this chapter we'll discuss each of these aspects of preventive maintenance. But before we do this let's consider the second maintenance category, corrective maintenance.

When preventive maintenance or performance checks reveal that a casualty or malfunction exists in a system or equipment, some form of corrective maintenance is required. Corrective maintenance includes those activities required to restore fire control equipment to its designed capabilities or efficiency. This includes the repair of damage caused by wear, accident, or other cause.

Corrective maintenance is generally performed in three phases: (1) troubleshooting, (2) removal and replacement of parts, and (3) alignment and adjustment. Occasionally there is an overlap of some of the activities of preventive and corrective maintenance.

CLEANING AND LUBRICATION OF COMPUTING DEVICES

Many mechanical computing devices used in fire control equipment are highly machined and are close tolerance mechanisms. The accuracy of the fire control system is often dependent upon the operation of these mechanical devices. Dirt, dust, or other foreign particles will cause the system to operate inaccurately. Moisture may cause corrosion which may also cause inaccuracy. Excessive wear will cause inaccuracies and shorten the life of the equipment. Thus, it can easily be seen that cleaning, lubrication, and moisture-proofing of close tolerance parts is necessary to have accurate effective equipment.

Most mechanical equipment is enclosed in a dustproof housing. If you use reasonable precautions, the dust problem in this equipment is small. Before you remove a cover, be sure the surrounding area is clean and that all likely sources of dust have been eliminated. A major source of dust is the ventilation system. When working on precision equipment such as a computer, the ventilation system should be secured. If you cannot secure it, cover the blower duct openings with cheesecloth or gauze.

If a unit is removed from its housing and taken to a shop or other working area, adequate provisions must be made to keep the mechanisms clean and dry. Before the unit is disassembled, all dirt, dust, grease, and other foreign matter must be removed from its outside surface. The working surfaces of the unit, and the components or subcomponents to be worked on, must be as clean and dry as circumstances permit. Whenever the unit is disassembled, all components and subcomponents must be kept under lint-free dust covers (cloths) to protect them from foreign matter.

Cleaning

Even when the previous precautions are taken, some dirt and other foreign matter may penetrate into the equipment. Also, it may be necessary to remove excessive or old oil and grease. The solvent that should be used for mechanical parts is Federal Specification PS-661. If some other solvent is to be used, it will be specified by the ordnance publication applicable to the equipment. The correct solvent MUST be used since some solvents leave a residue or cause corrosion. Therefore, ALWAYS check the OP.

Spraying or splashing of the solvent must be avoided during cleaning. If the solvent were to fall upon a bearing surface, it would cut or render the lubricant less effective, causing excessive wear. After the solvent has been used, the parts must always be wiped dry with a clean lint-free cloth.

MOISTURE.—The battle against moisture is never-ending. Moisture creeps into the smallest openings. Watertight covers must be kept watertight. When you remove a cover, check the condition of the gasket, the knife edge, and the securing bolts or dogs. Where possible, when checking an electrical circuit, use a connection box in a protected space. When moisture is discovered in an instrument or connection box, dry it out with a hot-air blower or an electric lamp.

A reasonable degree of protections against the accumulation of moisture is obtained by a daily energizing and workout of the equipment.

Variations in temperature cause air to be breathed through any opening or vent in the equipment. As the temperature rises, the air inside a piece of equipment expands and is partly expelled. When the temperature falls, the air inside the equipment contracts and outside air is admitted. As the air cools, condensation or sweating takes place. Electrical heaters are installed in some instruments to eliminate this source of moisture. The heater keeps the interior of the instrument at a temperature higher than that of the surrounding air. In many instruments, the circuit to the heater bypasses the power switch, and voltage may be present even though the power switch is off.

Remember this when working around the heater circuit.

Some lead-computing sights use an air drier, or desiccator unit, to moistureproof the mechanisms within the unit. The unit is sealed by dust covers and is airtight except for the connection to the air drier. The air drier consists of a unit that contains silica gel crystals. The silica gel crystals absorb moisture from the air within the unit.

SALT AND FUNGUS.—Salt and fungus found in your equipment should be removed immediately. Salt, when moisture is present, will corrode metals and is a conductor of electricity. Fungus growth causes decay, rapid deterioration of insulating materials, and shorts or grounds in electrical circuits. Under some circumstances you can use fresh water to remove them. After cleaning the equipment, however, make sure the water is completely evaporated. A cleaning solvent, methyl chloroform, can be used to clean away salt or fungus. But methyl chloroform will attack electrical insulating materials and contact time should be limited. High concentration of methyl chloroform vapor can be dangerous to life. Adequate ventilation is necessary when it is used.

Lubrication

Lubricants are used to reduce friction between moving parts. Occasionally, lubricants are used for the purpose of preventing rust, oxidation, and corrosion. The applicable maintenance manual includes the lubrication instructions for the particular equipment. But no lubrication procedure will be effective unless it is performed regularly. Different components must be lubricated at different intervals; the recommended frequency of lubrication for each component must be followed.

Lubrication instructions are issued for all ordnance equipment. Most of these instructions are in the form of charts in the equipment's OP. OD 3000 gives general lubrication instructions for ordnance equipment.

Lubrication charts indicate the type and amount of lubricants, lubrication points, and frequency of application. In addition, the charts may contain other maintenance functions to be performed in conjunction with lubrication. Don't trust your memory, use the charts and a checkoff list with a systematic schedule.

Do not overlubricate your equipment. Excessive lubricant acts as an insulating blanket and prevents the dissipation of heat. Overfilling or overheating may cause overflow into adjacent electrical equipment. Lubricants generally deteriorate electrical insulation materials.

Cleanliness is important in lubrication. Dirt in a lubricant makes a damaging abrasive material. Plastic protective caps are provided for some types of grease fittings. Lubrication points must be cleaned prior to lubrication. If a cleaning solvent is used it must be wiped dry before the lubricant is applied.

CLEANING AND LUBRICATING ELECTRONIC EQUIPMENT

Most electronic equipment has a serious dust problem. This is a direct result of the heat problem. Heat is dissipated by air taken into the unit and circulated. Air filters are installed, but they are not 100 percent effective. The housing is not dustproof, so you can expect to find some dust in electronic units.

You should clean electronic units frequently. To clean an electronic assembly, use a soft brush and a vacuum cleaner with a nonmetallic hose. Keep in mind that even though the power is off, dangerous potentials may still be present.

Avoid using a portable blower or a compressed air hose to clean a cabinet or chassis. Dust may be blown into relay contacts or open switches. Oil inside the cabinet will usually be caused by a leaky oil-filled capacitor, which should be found and replaced.

Air filters must be cleaned periodically. They are often neglected or disregarded until excessive heating causes a breakdown of the equipment. Accumulated dust is removed by hosing the filter with soapy water. The filter is then dried, and reoiled with light machine oil.

Ceramic insulators should be kept clean to prevent leakage and possible arc-overs. If wiping with a clean cloth is not enough, a cloth moistened with an approved solvent may be used. The insulator is then polished dry with another clean cloth.

Ferrule resistors and fuses should be removed from their clips, and corrosion or dirt removed from the components and clips. Use a cloth dipped in solvent, or if necessary, fine sandpaper or crocus cloth to remove the dirt.

Electronic equipment is more than an arrangement of vacuum tubes, transistors, and other electronic units. Its operation depends upon a number of moving mechanical parts. Many of these parts require lubrication at regular intervals. The OP for each electronic equipment gives the lubrication instructions, usually in chart form. Lubrication techniques are the same for electronic equipment as they are for mechanical equipment.

INSPECTIONS

To prevent the likelihood of future troubles or malfunctions you must make visual inspections of your equipment. In the following paragraphs we will point out some of the things you should look for.

Routine visual inspection of terminal boards should be made and terminal screws checked for tightness. A loose terminal lug can cause an intermittent malfunction of equipment that may be difficult to find. It is important not to overtighten terminal screws because you may strip the threads. Loose terminal lugs are a common source of trouble because they work loose due to normal ship vibration.

Cables should be inspected for looseness or damage at places where they enter equipment or at any other point in a cable run. Cables showing signs of damage or abuse should be either rerouted or protected. Particular attention should be given to the coaxial cable, which is easily damaged by dents or sharp bends.

Look for signs of overheating and faulty insulation. When these signs appear, the equipment will be blackened around the area of overheating. Check the condition of tubes and tube sockets. Sometimes the shock of gunfire loosens the tubes in their sockets.

The air screens of amplidyne motors and motor generator sets should be inspected and kept cleared of dirt and dust. Excessive vibration of these units is a danger signal of faulty operation. The most usual causes are loose mounting bolts, shaft misalignment, and foreign matter rubbing the rotating element.

Inspect junction boxes, exposed radar compartments and other unit covers to see that they are properly dogged down. Tighten all retaining bolts and dogs evenly and firmly, alternating between diametrically opposite bolts or dogs.

PERFORMANCE TESTS

If all fire control equipment, including connecting cables, could be enclosed in a dehydrated chamber and protected against shock and vibration, perhaps performance checks would not be so important. Since the equipment is not enclosed, good preventive maintenance practice requires that you OPERATE and TEST all equipment and instruments DAILY, if possible.

The performance tests are an important part of the 3M maintenance system. We refer only to the 3M system since it will soon be the only maintenance system, but the tests are a part of all the systems. The performance tests are completely integrated into the 3M system. The test results are recorded on checkoff sheets or forms provided by the 3M system, by BuWeps or by the type command. By keeping a record of your tests, not only will you have a day-to-day reference of the system's performance but you will be able to detect failures and malfunctions as they occur.

We will discuss in general terms some of the tests with which you will be required to help, or to record the results.

Transmission Tests

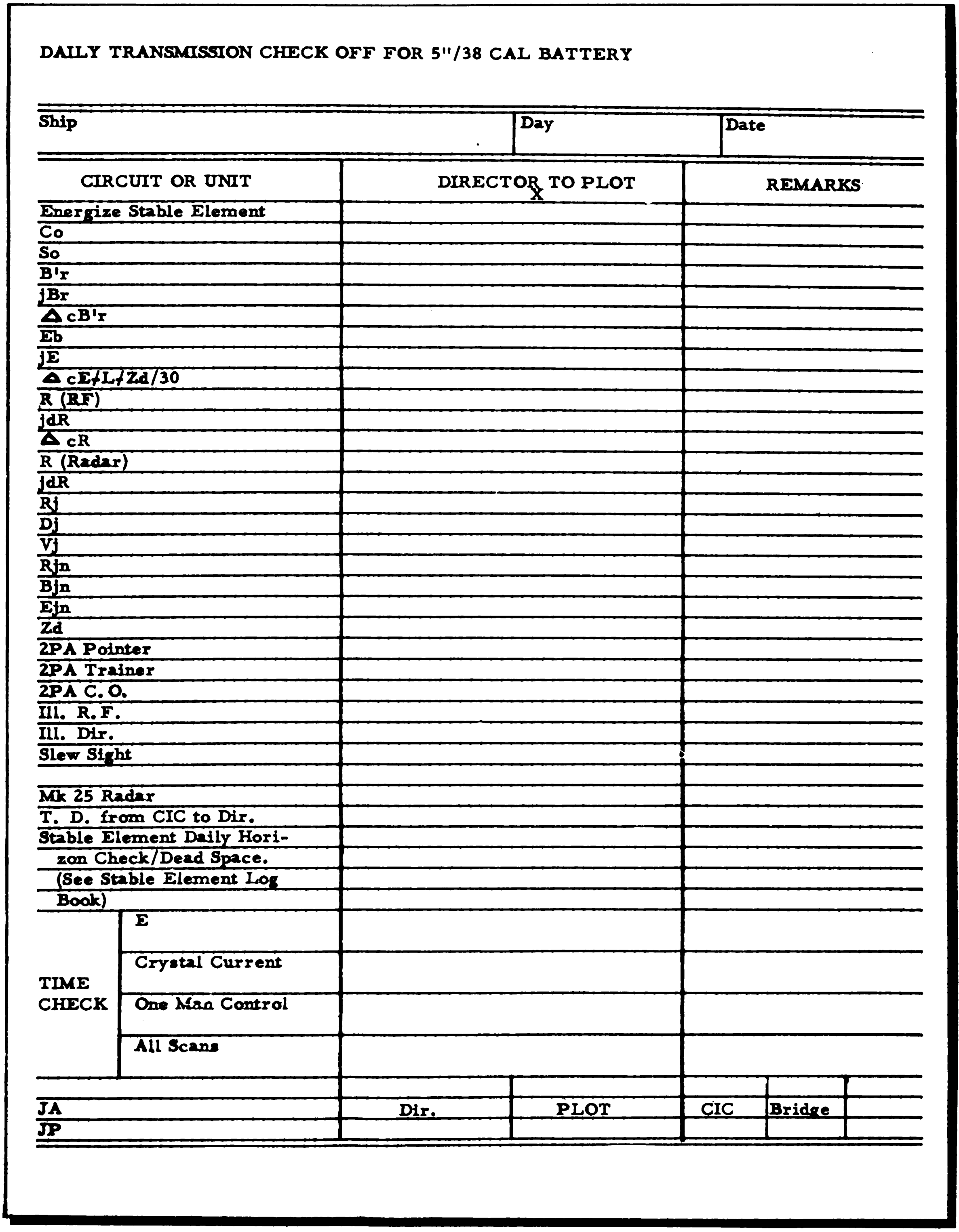
The transmission test is held daily. It tests the accuracy of the information flow between instruments and stations, and the response of automatic control devices and power drives to changing signals. In addition, many routine daily checks are included. Figure 17-1 is a portion of a transmission checkoff sheet. From the illustration you can get a good idea of the type of items checked in this test.

Daily operation of the system in all modes of control exercises the servosystems, power drives, and computing networks. These exercises help to avoid some casualties and detect existing casualties.

Operational Tests

Operational tests are among the most important checks of the fire control equipment. The final test of your equipment is its operational performance. All fire control equipment should be tested periodically, as both an individual unit and a part of the system. To hold these tests correctly, the operators must be thoroughly familiar with the operating characteristics of the equipment in all types of control. Following is a list of a few items that will not necessarily be checked by the other tests, although they can and should be tested by the operators on stations.

1. The entire system tracking a target.
2. Target designation system or weapons directional equipment and all indicators.



DAILY TRANSMISSION CHECK OFF FOR 5"/38 CAL BATTERY

Ship	Day	Date

CIRCUIT OR UNIT		DIRECTOR TO PLOT X	REMARKS
Energize Stable Element			
Co			
So			
B'r			
jBr			
△cB'r			
Eb			
jE			
△ cE+L+Zd/30			
R (RF)			
jdR			
△ cR			
R (Radar)			
jdR			
Rj			
Dj			
Vj			
Rjn			
Bjn			
Ejn			
Zd			
2PA Pointer			
2PA Trainer			
2PA C. O.			
Ill. R. F.			
Ill. Dir.			
Slew Sight			
Mk 25 Radar			
T. D. from CIC to Dir.			
Stable Element Daily Horizon Check/Dead Space. (See Stable Element Log Book)			
TIME CHECK	E		
	Crystal Current		
	One Man Control		
	All Scans		

JA	Dir.	PLOT	CIC	Bridge	
JP					

55.309

Figure 17-1.—Portion of a transmission checkoff for 5''/38 battery.

3. Interbattery connections and flow of information.
4. Special purpose computers: starshell, shore bombardment, wind, parallax.
5. Optical equipment—rangefinder and rangefinder operators, stabilizers, lead-computing sights. The operational performance of fire control equipment is described in the OPs on the system and units.

Written instructions for operating the equipment are installed (cemented) on all ordnance equipment. These instructions, appropriately enough, are called Operating Instructions. They include the procedure required to energize, operate, and secure an equipment. It should be emphasized that the instructions do not stand alone; some knowledge of equipment operation must be possessed by the technician.

Frequently, operating instructions can serve as a valuable training aid. A technician who is expert in the operation of an equipment can train a man to operate a piece of gear by using the operating instructions as a guide. Thus, the trainee can refresh his memory from time to time by rereading the step-by-step instructions as he operates the equipment.

The operating instructions are sometimes printed on small cards so that they can be conveniently carried in a pocket of a uniform.

Daily Systems Operability Test

In the 3M maintenance system all the circuits and components in the weapon system were studied to determine their test requirements. The study was based on the function of each element of the weapon system and resulted in the Daily System Operability Test (DSOT). DSOT provides a single-source planning of tests for the entire weapon system and ensures that all the elements of the system are tested and serviced at the required frequency. Single-source planning reduced the number of required tests, and provided the additional dividend of keying the test results directly to troubleshooting procedures.

DSOTs check the system's operation by simulating an engagement against a static (stationary) target. The results indicate a success or failure of operation at key points throughout the test. Failure of an indication provides a reference point from which to begin troubleshooting. Supplementary tests are provided in the testing schedule to check the elements and modes of system operation not covered by the DSOT.

ROUTINE MAINTENANCE OF COMMON ELECTRICAL COMPONENTS

FUSE AND CIRCUIT BREAKER MAINTENANCE

The maintenance of fuses is a very simple operation. Since many fuses are designed with a glass body, a visual inspection will normally disclose an open fuse. If there is any doubt as to the condition, a continuity test will readily indicate an open or closed fuse. If the fuse is defective, replace it with one of the same rating.

Occasionally the fuse holders will become defective. Here, once again, the maintenance required is a visual inspection followed by a continuity test. Broken wires, cold solder joints, and broken or missing parts can usually be detected by a visual inspection. A continuity test will indicate the condition of the connection and show if any opens exist. If the holder is found to be defective, it should be replaced.

Circuit breaker maintenance presents a little more difficulty due to the possibility of a change in current capacity. This change may result from usage over a period of time and is difficult to detect. If the current carrying capacity increases, the circuit protection value will be reduced. If the current carrying capacity decreases, the circuit breaker will open with less than rated current. Normally, under this condition the circuit breaker is the last component suspected because its opening usually indicates a circuit failure.

The usual maintenance of breakers involves a visual inspection of the terminals and resistance checks. These tests will indicate an open, shorted, or grounded condition. If a breaker malfunctions or appears to be operating improperly, it should be immediately removed and replaced by a new unit of the same type and rating.

SWITCH MAINTENANCE

While the switch itself is relatively simple to check, it sometimes offers difficulty in maintenance because it is inaccessible. After a visual inspection of the connections and the switch, a continuity test will indicate any malfunctions. When the switch mechanism is found to be defective, it normally is not repairable and therefore should be replaced.

When enclosed switches are used, failure to seal properly around cable openings causes the most difficulty. Atmospheric changes permit "breathing" of moist air into enclosures with improperly sealed cable openings, and the moisture in the air may condense within the switch enclosure. The condensation can short across the switch terminals and can corrode the switch actuators. This difficulty can be corrected by careful sealing of openings. Hermetically sealed switches will prevent dust, dirt, and moisture from entering the switch.

Some switches depend upon pressure for their operation. These switches have adjustments so that they will operate at the correct time or pressure. In many cases if the adjustments are not accurate, damage can result.

RELAY MAINTENANCE

The relay is one of the most dependable electromechanical devices in use, but like any other mechanical or electrical device in fire control equipment, relays occasionally wear out or become inoperative for one reason or another. Should relay inspection show that a relay has exceeded its safe life, the relay should be removed immediately and replaced with another of the same type. Care should be exercised in obtaining the same type replacement because relays are rated in both potential relay trouble.

As guides for spotting potential relay trouble during preventive maintenance, the following are suggested. Check for charred or burned insulation on the relay. Check for darkened or charred terminal leads coming from the relay. Both of these indicate overheating. If there is even a slight indication that the relay has overheated, it should be replaced with a new relay of the same type. An occasional cause of relay trouble is not the fault of the relay at all, but is due to overheating caused by the power terminal connectors not being tight enough.

It is not recommended that covers be removed from semisealed relays in the field. Removal of a cover in the field, although it might give useful information to a trained eye, may result in entry of dust or other foreign material which may cause contact discontinuity. What is even more serious, removal of the cover may result in loss of or damage to the cover gasket. One of the prime advantages of hermetically sealed relays is that they cannot be taken apart.

Relays can be ruined by the use of sandpaper or emery cloth for cleaning the contacts. A BURNISHING TOOL should be used for this purpose. Two types of burnishing tools are stocked at naval supply activities; and either type can be obtained through regular supply channels. The appearance and use of one kind of burnishing tool are shown in figure 17-2A. The surfaces of the tool that are used to clean the relay contacts should not be touched by the fingers prior to use; and after use, the burnisher should be cleaned with alcohol.

When relays contain bent contacts, no attempt should be made to straighten them with long-nose pliers. Such an attempt often causes further damage with the result that the entire relay must be replaced. Bent contacts can be straightened effectively by using a CONTACT BENDER. The bender can be made locally from 0.125-diameter rod stock according to the dimensions shown in figure 17-2B.

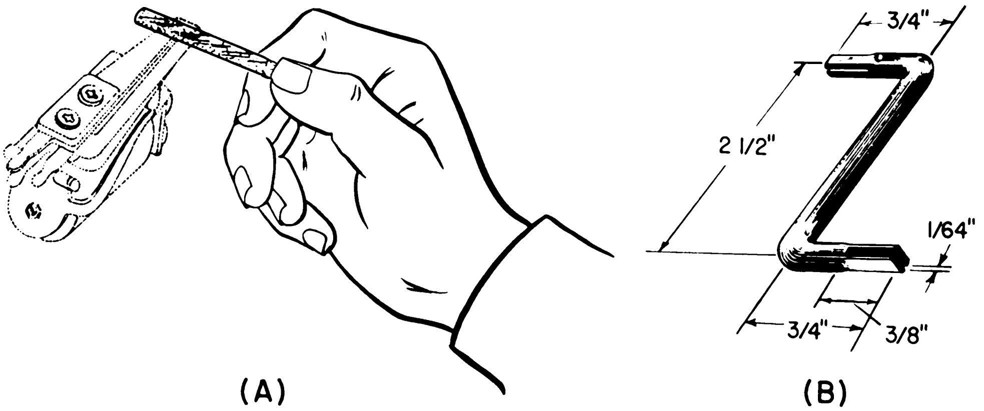


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Figure 17-2.—Relay special tools. A. Burnishing tool. B. Point bender.

POTENTIOMETER AND RHEOSTAT MAINTENANCE

In both preventive and corrective maintenance, the first step to be undertaken is a thorough visual inspection. Such an inspection should reveal any improper soldering, loose connections, or broken leads. It will also disclose any overheating which results in charred, discolored, or blackened terminals, connectors, or leads. Another step in the maintenance of rheostats and potentiometers is to check, where possible, for binding or uneven motion of the wiper contact. A word of caution here: adjustments should never be needlessly changed.

Other checks of these variable resistors are tests for shorts, opens, and grounds. An ohmmeter should be used to measure the actual resistance between terminals. Resistance measurements, while the device is still connected in the equipment, may result in incorrect readings because of other components in parallel with the measured device. If the potentiometer or rheostat is found to be defective either electrically or mechanically, it should be replaced with another of the same type.

ROTATING MACHINERY MAINTENANCE

Rotating machinery should be inspected and cleaned at prescribed intervals (periodic checks) and whenever repairs to the machinery have been made. For such cleaning and inspection, the following procedure is suggested.

1. Unfasten and remove end cover.
2. Remove dust and dirt from machine and end covers, using clean, dry compressed air or a soft brush.
3. Loosen, gently remove, and inspect brushes, being extremely careful not to nick or mar their edges. Note the location and position from which each is removed so that it can be replaced in exactly the same position.
4. Check commutators or sliprings for excessive wear, pitting, dirt, thrown solder, or other defects. A highly polished commutator or slipring is desirable, but a dark-colored one should not be mistaken for a burned one. If the surface is dirty, clean with a lint-free cloth moistened in a cleaning solution (Specification PS-661) and wipe dry. Avoid fingermarking the commutator or slipring surface.
5. Secure all brushes in their holders, making certain they are replaced in exactly the position from which they were removed.
6. Replace and secure end covers.

Sliprings

Sliprings are solid metal rings mounted on the rotor of alternating current machines for transferring the power to or from external circuits through brushes or wipers. Sliprings are also used on synchros, director connections, and stable element connections.

While they vary in size and type, the maintenance of sliprings is essentially the same for all types. They should be inspected periodically for wear, grooving, and cleanliness. Normally, the surface of the rings should be bright and smooth.

As mentioned previously, the connection to the rings is by brushes or wipers. Wiper contacts are used with devices that do not require high current and consequently require only light pressure when making contact. Excessive pressure will result in excessive wiper wear, because the wiper contact is usually of a softer material than the rings. Any contacts showing considerable wear should be replaced.

If sliprings are inspected and found rough, scratched, or grooved, corrective action must be taken. They can be smoothed with a fine crocus cloth or sandpaper. However, care should be exercised not to cause high and low spots which will interfere with high speed operation. Further repairs, such as cutting with a lathe, should be performed at overhaul activities (Navy yards and tenders). Also in cleaning with a solvent, be careful not to allow the solvent to enter the bearings since the solvent will cut oil or grease. This, of course, will cause the lubricant to flow out of the bearing.

Commutators

Commutators have been called the "soft spot" of d-c machinery because they require considerable maintenance. The commutator is a series of copper segments separated by an insulator. When the brushes make contact with a pair of segments, an armature coil is connected into the circuit. Thus when the motor or generator is moving, the brushes and commutator switch coils in and out in the proper sequence.

The normal appearance of the commutator is a shiny, smoothly worn, chocolate brown color. A blackened or pitted commutator is caused by poor brush and segment contact, open or shorted coils, overloads, etc. If the brushes are causing the blackened appearance, they should be replaced and then the commutator should be cleaned. Cleaning is accomplished by the use of fine sandpaper and the recommended solvent. The sandpaper should be held against the commutator by a piece of wood that is grooved to fit the commutator. NEVER USE EMERY CLOTH. Emery is an electrical conductor, which will cause a short circuit.

If the fault is other than brush and segment contact, that is a short or open coil, the machine should be replaced and sent to overhaul. Another fairly common defect is HIGH MICA. As the copper of the commutator wears down, the mica, which is the insulation separating the segments, does not. Consequently, it may be higher then the segments. The high mica gives a bounce to the brush every time it passes underneath; this results in arcing because the brush is constantly breaking contact. High mica can be spotted by rubbing your fingernail over the surface of the commutator. There should be a small depression between each segment. If there is high mica, this depression disappears. Undercutting is the remedy for high mica, and this operation is normally reserved for the overhaul activities.

Brushes

Brushes are found in numerous sizes and shapes and are made of various materials and compounds. Many brushes used in fire control equipment are made of a composition of graphite and other forms of carbon. In all probability the majority of the maintenance you will perform on rotating machinery will be concerned with brushes. Brushes should be checked for wear, chipping, oil soaking, sticking in the brush holders, spring tension, length, and area of contact with the commutator. If for any reason a brush is removed and is to be replaced, it should be marked or tagged so it may be replaced in the same brush holder in the same position it occupied before removal.

Brushes that show excessive or improper wear, chipping, or are oil soaked, should be replaced. Care should be exercised in obtaining the correct replacement. It is important that the brushes be changed before they are completely worn away in order to prevent damage to the equipment in which they are used.

Some brushes are marked to indicate allowable wear by a readily noticeable groove in their edge. This groove extends from the top of the brush down to a point that is 75 percent of the brush wearing depth. (The top is the end opposite the wearing face.) Thus if the brush is worn down to the groove, it must be replaced. If no groove is present, consult the equipment OP for acceptable minimum brush lengths.

In the replacement of brushes, you will find that some new brushes are ready to use. That is, the brush face is slightly concave so that it fits tightly on the commutator. However, because other new brushes are NOT ready for use, they must be sanded in. This sanding, or seating, can be accomplished by wrapping fine sandpaper around the commutator. The paper is placed sand side up with a lap following the direction of normal rotation of the device, and is held in place by a rubber band. Do NOT use glue or tape. The brushes are placed in their holder under spring tension, and the armature is rotated slowly by hand in the direction of normal rotation. In so doing, the contact surfaces of the brushes are sanded until their curved surfaces match the curvature of the commutator. The carbon dust from the brushes must be removed from the device by using dry compressed air followed by cleaning with solvent.

MAINTENANCE TECHNIQUES

SOLDERING

The correct procedure for soldering is given in Basic Electricity, NavPers 10086-A; therefore, it will not be covered here. Let us consider for a moment the end product—properly and improperly made soldered joints.

A good well-bonded connection is clean, shiny, smooth, and round. It shows the approximate outline of the wire and terminals. The wire and terminals are completely covered, and the solder adheres firmly. The insulation is close but not in the hole or slot; it is approximately 1/8 inch from the terminal. It is not charred, burned, nicked, or covered with rosin. A film of rosin may remain on the joint and need not be removed unless the joint is in a high frequency circuit or unless fungusproofing is anticipated.

Soldered joints may be defective for a variety of reasons, such as the following.

A COLD solder joint has a dull appearance and a crystallized texture. Because of the poor union between the wire and terminal, the joint will in time develop high resistance as the metals oxidize. This type of joint is caused by insufficient heat during soldering, and may be repaired by reheating.

A ROSIN joint is so named because the wire is held by rosin rather than solder. The flux is spread over the terminal, and instead of the solder bonding with the terminal, the solder settles on top of the rosin. The joint may have all the appearances of a good joint, but a little pressure will cause movement or an ohmmeter will indicate an open. A rosin joint occurs when using a "cold" iron or one that is too small. In most cases, merely applying a hot iron will clear up a rosin joint.

A DISTURBED solder joint has an irregular or crystallized appearance and the solder may be chipped off with a fingernail or a pointed tool. It is caused by the wire being moved before the solder has fully set. It may be repaired in the same manner as the cold solder joint.

An INSUFFICIENT solder joint can introduce high resistance in the circuit and, as current flows, undesirable heat. It may loosen and cause an open or intermittent operation depending upon the amount of oxide present. This heat or a visual inspection may reveal this condition, but it may be necessary to use an ohmmeter to detect this type of solder joint. To repair it, it should be taken apart; and after cleaning off the oxide, the joint should be resoldered correctly.

A NO-SOLDER joint may cause noise due to oxide or vibration; the circuit may open entirely. A visual inspection and an ohmmeter will indicate this condition. The joint should be taken apart, cleaned, and then resoldered correctly. There are many other soldering defects, such as excessive solder, loose solder, and insulation too close or too far from the joint.

Occasionally some special techniques are required in soldering. Such an occasion occurs in fire control equipment using miniaturized components. In such equipment, the physical dimensions of resistors have greatly decreased and application of a soldering iron close to the body of these small carbon composition resistors causes a PERMANENT change in resistance. Overheating of these resistors and other components during soldering can be avoided only by restricting heat conduction along the terminating leads.

The most acceptable means of preventing this overheating is by use of a thermal shunt, (fig. 17-3). This shunt should be placed as close to the resistor and as far from the joint as possible. Be certain that the clamp does not contact both the resistor and the joint. If you don't have a clamp type shunt, and don't have time to make one, you can use small needle-nose pliers. If you wrap a rubber band tightly around the handles, the pliers will grip the resistor lead so that you won't have to hold them in place while you solder.

CRIMPING

The crimp-on or solderless terminals require relatively little operator skill. Another advantage is that the only tool necessary is the crimping tool. The connections are made more rapidly; they are cleaner and more uniform. Due to the pressures exerted and the materials used, the crimped connection or splice, properly made, has an electrical resistance that is less than that of an equivalent length of wire.

The basic types of terminals are shown in figure 17-4. A shows the straight type, B the right angle type, C the flag type, D the splice type, and E the disconnect splice type. There are also variations of these types, such as the use of a slot instead of a terminal hole, three- and four-way splice type connectors, etc.

Various size terminal or stud holes will be found for each of the different wire sizes. A further refinement of the solderless terminals is the insulated terminal; the barrel of the terminal (fig. 17-4) is enclosed in an insulation material. The insulation is compressed along

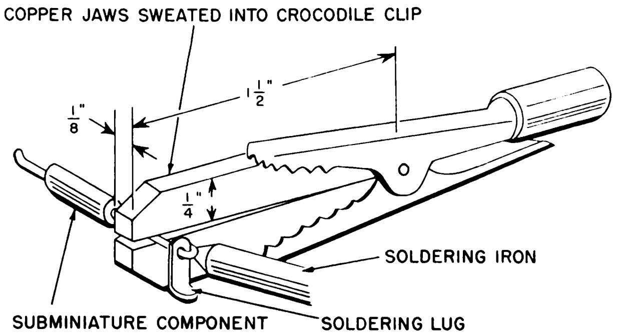

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Figure 17-3.—Details of thermal clamp type shunt.

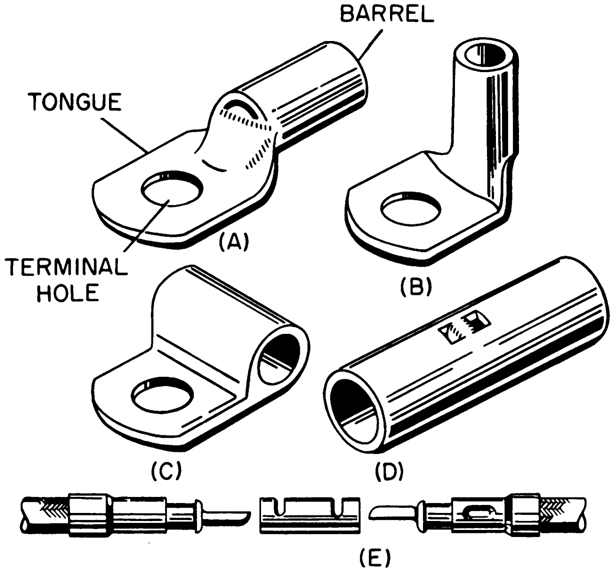

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Figure 17-4.—Basic types of solderless terminals.

with the terminal barrel when crimping, but is not damaged in the process.

This eliminates the necessity of taping or tying an insulating sleeve over the joint.

There are two types of crimping tools used with copper terminals. For wire sizes AWG (American Wire Gage) 10 or smaller, a small pliers type of crimper is used. For the larger wire sizes, a large and powerful pincer type crimper is used. The small pliers type crimper has several sizes of notches for the different size terminals. The large pincer type is adjusted to an index mark for the different size terminals. Care should be exercised to select the correct crimping tool for the particular terminal. Do not tin stranded wires. (The solder forms a line of stress concentration on each strand, which may result in vibration failure.) Always use insulation-grip terminals for wire sizes No. 10 AWG and smaller, regardless of application, to protect conductors from mechanical vibration and fatigue.

The procedure for crimping a copper terminal to a copper wire is as follows:

1. Strip the cable insulation carefully to avoid cut or nicked strands. Remove the proper length of insulation.
2. See that the stripped cable end extends into the terminal barrel for the full length of the barrel.
3. Center the terminal barrel in the crimping tool so that pressure on the strands, from the crimped strands to the unsecured strands, will be gradual, thus preventing stress concentrations.
4. Now crimp the terminal, making sure that the crimper is fully closed to ensure proper crimping.
5. Inspect the joint with a probe through the inspection hole. The end of the conductor must come to the edge of the inspection hole.

If the correct tools are used, and the proper procedures followed, the connections will be more effective electrically, as well as mechanically, than soldered connections. A visual inspection is very important for it will reveal oxidation, deterioration, overheating, and broken conductors. In some cases it may be necessary to check these connections with an ohmmeter; the proper resistance, for all practical purposes should be zero. Any defective terminal should be removed and a new terminal crimped on.

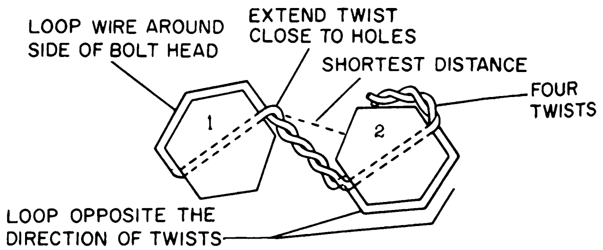
SAFETY WIRING

Screws, bolts, electrical and mechanical connectors, and other devices are safety wired as an additional security against the effects of vibration. Figure 17-5 shows the basic principles of safety wiring. The wire is threaded through the bolthead in such a direction that if a bolt tends to loosen, the wire will become tighter.

The wire used in safety wiring is usually made of annealed brass or annealed stainless steel. The size is not critical, depending mainly on the size of bolt being secured. The bolt used has a hole drilled through the head.

Refer to figure 17-5. The general procedure for safety wiring is as follows:

1. Thread the wire through the first bolt.
2. Loop the wire around the side of the bolthead. The loop should be opposite the direction followed by the twisted wire so as not to


LOOP WIRE AROUND SIDE OF BOLT HEAD
EXTEND TWIST CLOSE TO HOLES
SHORTEST DISTANCE
FOUR TWISTS
1
2
LOOP OPPOSITE THE DIRECTION OF TWISTS

12.245

Figure 17-5.—Safety wiring.

interfere with it. Never kink the wire as it will be weakened at this point.

3. Twist the wire by hand; hold the wires so that an angle of about 90 degrees is formed between them. Do not use pliers as this tends to develop kinks and nicks, and to make the twist too small and tight.

4. Thread one end through the second bolthead, and the other end around the side of the bolthead that is opposite to the direction of the twisted wire.

5. Pull both ends tight, and give a minimum of four twists on the far side of the second bolt.

6. Cut off the wire and bend it along the side of the bolthead.

Under conditions of severe vibration, the coupling nut of the AN connector may vibrate loose; and with sufficient vibration, the connector will come apart. When this occurs the circuit carried by the cable will open. The proper protective measure to prevent this occurrence is a safety wiring attachment as shown in figure 17-6. Remember, any time a safety wire is NOT replaced a failure may result.

The safety wire should be as short as practicable and must be installed in such a manner that the pull on the wire is in the direction which tightens the nut on the plug.

TYING AND LACING

While making repairs or fabricating a new cable, it may be necessary for you to tie or lace the cable. The accepted method for lacing cable harnesses is shown in figure 17-7A. The use of the continuous lacing method is restricted to panels and junction boxes. The purpose of lacing is to keep all cables neatly secured in groups and to avoid possible damage from chafing against equipment or interference with equipment operation. When continuous lacing is used, it shall not include cables of more than one harness group.

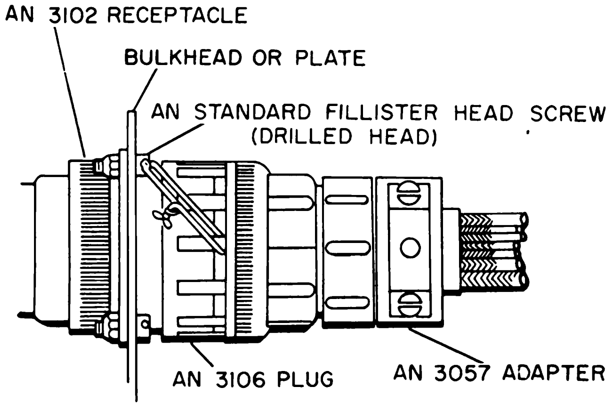


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Figure 17-6.—Safety wiring attachment for plug connectors.

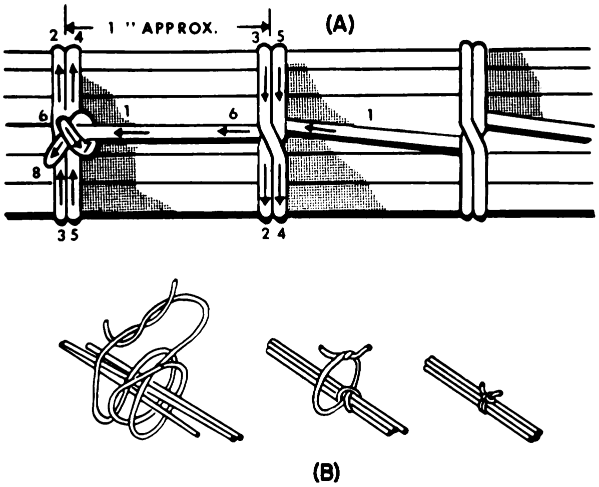

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Figure 17-7.—Lacing and tying.

Because continuous lacing has the disadvantage that if the cord is broken the lacing has a tendency to unravel, it is restricted in its use. In place of continuous lacing, tying (or short-section lacing) is used. The method of tying in use is shown in figure 17-7B. In the first method, tie a clove hitch about the wires. Then tie a half hitch over the clove hitch in such a manner as to produce a square knot.

SHIELDING AND BONDING

Shielding is the enclosing of cables or electrical units in metal to prevent high frequency interference. Shielding causes the high frequency voltage to be induced in the shield rather than in the units or cables. Shielding is used where a unit is to be protected from radio frequency noise. It is also used to keep cables or units from emitting radio frequency noise.

Where shielding of cables is used, it is very important that it be well grounded. Radiating circuits such as pulse cables and transmission lines use coaxial cables. The outer flexible conductor of "coax" often serves as the shield, but occasionally an additional braid is used for shielding. Regardless of the system used, the conductor forming the shield is grounded.

Disturbances caused by spark discharges are the most difficult to control. A spark discharge not only radiates but also causes voltage variations in the circuit. Shielding is effective for the radiations but not for line variations. These variations in the line can be smoothed out by the use of filters. The function of such filters is to block or bypass voltages and currents of frequencies which would cause interference.

Bonding straps are used to tie together, electrically, any parts of an equipment or system which are insulated from the ship's structure. Bonds are used, for example, to connect the various panels and computers of the Mk 56 GFCS to the ship's structure. Some of the reasons for bonding are:

1. to minimize interference to electronic equipment by equalizing the static charges that accumulate.
2. to provide a proper "ground" for electronic equipment.
3. to provide a low resistance return path for single-wire electrical systems.
4. to aid in the effectiveness of shielding.

A bond is usually made of a flexible metal strap provided with a crimped-on terminal at each end.

The bond must be intact and make a good electrical connection at all times. In replacing a bond, be careful to make a good metal contact. Place bonds in such a position that they will not interfere with the operation of the unit and will not be damaged or broken loose because of the motion or vibration of the unit.

CABLE SPLICING

Cable splices should not be used except as an EMERGENCY measure.

A splice should give a good electrical and mechanical joint and should be taped to give insulation equivalent to the rest of the cable. A permanent repair must be made as soon as it is possible. The two splices normally used by the Fire Control Technician are the "western union splice" and the "flexible wire splice." These and other splices and joints are covered in Basic Electricity, NavPers 10086-A.

WATERTIGHT BOXES AND FITTINGS

Aside from mechanical injury, the biggest source of electrical trouble on board ship is moisture. And salt water moisture is the worst kind because it is a conductor of electricity. Thus, when a cable or box becomes saturated with salt water, two things happen: First, a current path to the ship's hull is formed which is a ground; and second, especially where dissimilar metals are involved, electrolysis and corrosion occur, and the connections or wire fittings are slowly eaten away. Therefore, practically all of the electrical wiring aboard ship is run in waterproof, fire-resistant, armored cables which terminate in watertight boxes.

The cables are run into boxes through stuffing tubes, also called terminal tubes. When renewing cable these tubes must be repacked with a standard packing corresponding to the size of tube, and the packing ring and nut must be tightly secured. Figure 17-8 shows a cross-sectional diagram of a stuffing tube properly assembled with an armored cable in place. Stuffing tubes similar to the one shown are used to ensure watertight integrity where cables pass through decks and bulkheads. Where cables pass through the deck, pipe risers are used in order to prevent mechanical injury to the cable. The stuffing tube is then inserted at the top of the pipe.

Terminal and junction boxes used for most fire control work are rated according to the number of terminals they contain, for example, 10-wire box, or 50-wire box. All wires are lugged at the ends to ensure solid connections at the terminal strips or blocks within each box. The lugs are, or should be, stamped with circuit designation numbers to assist the maintenance men in tracing out circuits. You'll find the cable leads laced together with cord and neatly

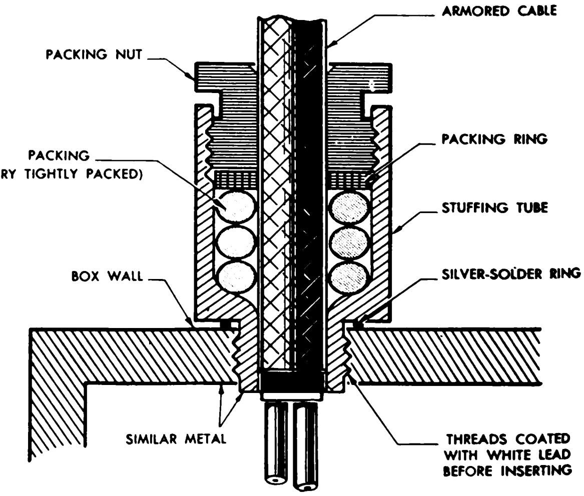

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Figure 17-8.—Watertight stuffing tubes.

arranged in each box to make for compactness. Always rearrange the box in this manner after pulling out leads for inspection, making tests, or relugging.

ELECTRICAL METERS

The construction and operation of electrical meters are covered in Basic Electricity, NavPers 10086-A. It should be emphasized that a thorough understanding of meters, coupled with the theory of circuit operation, is most essential in servicing and maintaining electrical equipment. Remember that the best meter available is of no use to the man who does not know what he is measuring or what the readings indicate. It is well to pay special attention to the meter coverage in the basic text and to their use as covered here.

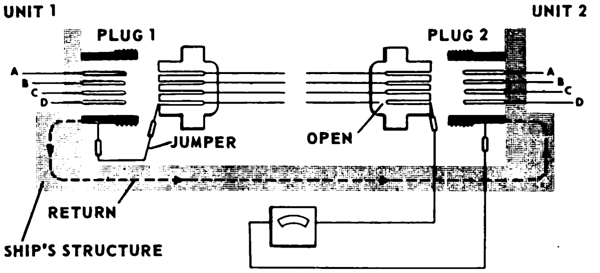
The techniques suggested here are not all-inclusive. You will find, as you develop your technical skill, there are other variations and techniques in use. As an example, consider the techniques for measuring current in a circuit. This can be done by placing an ammeter in series. It can also be accomplished by measuring the voltage across a resistor of known value. Then by application of Ohm's law, the current in the circuit can be calculated. This last technique has the advantage of eliminating the necessity of opening the circuit for placement of the ammeter.

CONTINUITY TEST

Open circuits are those in which the flow of current is interrupted by a broken wire, defective switch, or any means by which the current cannot flow. The test used to check for opens (or to see if the circuit is complete or continuous) is called CONTINUITY TESTING.

An ohmmeter (which contains its own batteries) is excellent for a continuity test. In an emergency a continuity test can readily be made using two sound-powered telephone handsets. Normally, continuity tests are performed in circuits where the resistance is very low (such as the resistance of a copper conductor). An open is indicated in these circuits by a very high or infinite resistance. Such a condition would be an open conductor.

The diagram in figure 17-9 shows a continuity test of a cable connecting two fire control units. Notice that both connectors are disconnected and the ohmmeter is in series with the conductor under test. The power should be off. Checking conductors A, B, and C, the current from the ohmmeter will flow through plug No. 2, through the conductor, and plug No. 1. From this plug it will pass through the jumper to the chassis which is "grounded" to the ship's structure. The metal structure will serve as the return path to the chassis of unit 2 completing the circuit to the ohmmeter. The ohmmeter will indicate a low resistance.



12.250
Figure 17-9.—Continuity test.

Checking conductor D in figure 17-9 will reveal an open. The ohmmeter will indicate maximum resistance because current cannot flow. With an open circuit, the ohmmeter needle is all the way to the left since it is a series type ohmmeter (reads right to left).

Where conditions exist that the ship's structure cannot be used as the return path, one of the other conductors may be used. For example (referring to figure 17-9), to check D a jumper is connected from pin D to pin A of plug 1 and the ohmmeter leads are connected to pins D and A of plug 2. This technique will also reveal the open in the circuit.

TEST FOR GROUNDS

Grounded circuits are caused by some conducting part of the circuit making contact either directly or indirectly with the metallic structure of the ship. Grounds may have many causes. The two most common are perhaps the fraying of insulation from a wire allowing the bare wire to come in contact with the metal ground and moisture-soaked insulation.

Grounds are usually indicated by blown fuses or tripped circuit breakers. Blown fuses or tripped circuit breakers, however, may also result from a short other than ground. A high resistance ground may also occur where not enough current can flow to rupture the fuse or open the circuit breaker.

In testing for grounds, the ohmmeter may be used. By measuring the resistance to ground of any point in a circuit, it is possible to determine if the point is grounded. By considering figure 17-9, one possible means of testing a cable for grounds can be seen. If the jumper is removed from pin D of plug No. 1, a test for grounds is made for each conductor of the cable. This is accomplished by connecting one meter lead to ground and the other to each of the pins of one of the plugs. A low resistance will indicate that a pin is grounded. Both plugs must be removed from their units; if only one plug is removed, a false indication is possible for a conductor may be grounded through the unit.

USE OF THE MEGGER

A thorough discussion of the operating principles of the megger is found in Basic Electricity, NavPers 10086-A. Briefly a megger is an instrument for measuring very high resistance (therefore, insulation resistance). It consists of a handdriven d-c generator and a suitable indicating meter together with the necessary resistors. The name MEGGER is derived from the fact that it measures resistances of many megohms.

The need for such an instrument exists because ohmmeters will not accurately measure these high resistances. The low voltage contained in an ohmmeter is not sufficient to move enough current through high resistances. The generator within the megger will supply enough voltage to cause a measurable amount of current to flow; the meter indications will be in megohms.

There are various resistance ratings of meggers with full scale values as low as 5 megohms, and as high as 10,000 megohms. Figure 17-10 shows the scale of a 100-megohm, 500-volt megger. Notice that the upper limit is INFINITY and that the scale is crowded at the upper end. The first scale marking below infinity represents the highest value for which the instrument can be accurately used. Thus, if the pointer goes to infinity while making a test, it means only that the resistance is higher than the range of the instrument.

There are also various voltage ratings of meggers (100, 500, 750, 1,000, 2,500, etc.). The most common type is the one with the 500-volt rating. This voltage rating refers to the maximum output voltage of the megger. The output voltage is dependent upon the speed of turning of the crank and armature. When the megger's armature rotation reaches a predetermined speed, a slip clutch will maintain the armature at a constant speed. The voltage rating is important, for the application of TOO high a voltage to even a good component will cause a breakdown. In other words, do not use a 500-volt megger to test a capacitor rated at 100 volts.

Meggers are used to test the insulation resistance of conductors. A record (Resistance Test Record, NavShips 531) of insulation resistance of power and high voltage cables, motor and generator windings, and transmission lines is maintained. These records will reflect fluctuations in resistance and aid in determining when the components should be replaced to prevent a breakdown.

PRECAUTIONS—Precautions to be followed in the use of the megger are listed below.

1. When making a megger test, the equipment must NOT be live. It must be disconnected entirely from its source of supply before it is tested.

2. Observe all rules for safety in preparing equipment for test and in testing, especially when testing installed high voltage apparatus.

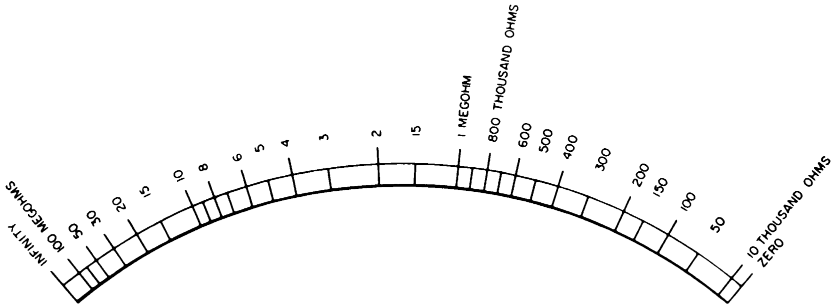


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Figure 17-10.—Megger scale.

3. Use well-insulated test leads, especially when using high range meggers. After the leads are connected to the instrument and before connecting them to the component to be tested, operate the megger and make sure there is no leak between the leads. The reading should be infinity. Make certain the leads are not disconnected or broken, by touching the test ends of the leads together while turning the crank SLOWLY. The reading should be approximately zero.

4. When using high range meggers, take proper precautions against electric shock, especially while the component is under test. There is sufficient capacitance in most electrical equipment to "store up" enough energy from the megger generator to give a very disagreeable and even dangerous electric shock. Owing to a high protective resistance in the megger, its open circuit voltage is not as dangerous, but care should be exercised.

5. Equipment having considerable capacitance should be discharged before and after making megger tests in order to avoid the danger of receiving a shock. This can be accomplished by grounding or short-circuiting the terminals of the equipment under test.

6. Meggers should not be used on some equipment. When in doubt, check the equipment OP.

TEST FOR SHORTS

A short circuit, other than a grounded one, is one where two conductors accidentally touch each other directly or through another conducting element. Two conductors with frayed insulation may touch and cause a short. Too much solder on the pin of a connector may short to the adjacent pin. In a short circuit enough current may flow to blow a fuse or open a circuit breaker. However, it is entirely possible to have a short between two cables carrying signals; such a short will not be indicated by a blown fuse.

As when checking for a ground, the device used for checking for a short is the ohmmeter. By measuring the resistance between two conductors, a short between them may be detected by a low resistance reading. In figure 17-9 by removing the jumper and disconnecting both plugs, a short test may be made. This is performed by measuring the resistance between the two suspected conductors.

Shorts are not reserved for cables; they occur in many components, such as transformers, motor windings and capacitors. The Major test method for detecting such components is to make a resistance measurement, and then compare the indicated resistance with the resistance given on schematics or in the equipment OP.

RESISTANCE TEST

Before checking the resistance of a circuit or of a part, make certain that the power has been turned off and capacitors in the associated circuit are discharged. To check continuity, always employ the lower ohmmeter range. If a high range is used, the meter may indicate zero even though appreciable resistance is present in the circuit. Conversely, to check a high resistance, use the highest scale, since the low range scale may indicate infinity though the resistance is less than a megohm.

In making resistance tests, take into account that other circuits that contain resistances and capacitance may be in parallel with the circuit to be measured, in which case an erroneous conclusion may be drawn from the reading obtained. Remember, a capacitor will block the d-c flow from the ohmmeter. To obtain an accurate reading if other parts are connected across the suspected circuit, one end of the circuit to be measured should be disconnected from the equipment. For example, many of the resistors in major components and subassemblies are connected across transformer windings. To obtain a valid resistance measurement, the resistor to be measured must be isolated from the shunt resistances.

Resistance tests are also used for checking a part for grounds. In these tests, the parts should be disconnected from the rest of the circuit so that no normal circuit ground will exist. It is not necessary to dismount the part to be checked. The ohmmeter, which is set for a high resistance range, is then connected between ground and each electrically separate circuit of the part under test. Any resistance reading less than infinity indicates at least a partial ground.

VOLTAGE TEST

The voltage test must be made with the power applied; therefore, the prescribed safety precautions MUST be followed to prevent injury to personnel and damage to the equipment. You will find in your maintenance work that the voltage test is of utmost importance. It is used not only in isolating casualties to major components but also in the maintenance of subassemblies, units, and circuits. Before checking a circuit voltage, a check on the voltage of the power source should be made to be sure that the normal voltage is being impressed across the circuit.

Obviously, the voltmeter is used for voltage tests. In using the voltmeter make certain that the meter used is designated for the type current (a-c or d-c) to be tested and has a scale of adequate range. Since defective parts in a circuit may cause higher than normal voltages to be present at the point of test, the highest voltmeter range available should be used at first. Once a reading has been obtained, determine if a lower scale can be employed without damaging the meter movement. If so, use the lower scale, so as to obtain a more accurate reading.

Another consideration in the circuit voltage test is the resistance and current in the circuit. A low resistance in a high current circuit would result in considerable voltage drop, whereas, the same resistance in a low current circuit may be negligible. Abnormal resistance in part of a circuit can be checked with either an ohmmeter or a voltmeter. Where practical, an ohmmeter should be used; the test is then carried out with the circuit "dead."

The majority of the electronics circuits encountered in fire control equipment will be low current circuits, and most voltage readings will be direct current. Also many of the schematics indicate the voltages at many test points. Thus if a certain stage is suspected and you desire to check the voltage, a voltmeter placed from the test point to ground should read the voltages as given on the schematic.

Many OPs also contain voltage charts where all the voltage measurements are tabulated. You will find more information on these charts later in this chapter. These charts usually indicate the sensitivity of the meter used to obtain the voltage readings for the chart. To obtain comparable results, the technician must use a voltmeter of the same sensitivity as that specified. Make certain that the voltmeter is not loading the circuit while taking a measurement. If the meter resistance is not considerably higher than the circuit resistance, the reading will be markedly lower than the true circuit voltage. (To calculate the meter resistance, multiply the rated ohms-per-volt sensitivity value of the meter by the scale in use. For example, a 1,000 ohms-per-volt meter set to the 300-volt scale will have a resistance value of 300,000 ohms.)

USE OF METERS

The following are guides for the proper use of meters.

1. An ammeter is always connected in series—NEVER in parallel.
2. A voltmeter is connected in parallel.
3. An ohmmeter is NEVER connected to a live circuit.
4. Polarity must be observed in the use of a d-c ammeter or a d-c voltmeter.
5. Meters should be viewed directly from the front. When viewed from an angle off to the side, an incorrect reading will result because of optical parallax.
6. Always choose an instrument suitable for the measurement desired.
7. Select the highest range FIRST and then switch to the proper range.

BRIDGE CIRCUITS IN METERS

An instrument employing a bridge circuit should be used in the measurement of resistance, capacitance, and inductance where a high degree of accuracy is desired. Bridge circuits are used in both a-c and d-c measuring instruments. Resistance, capacitance, and inductance bridge circuits are discussed in detail in Basic Electricity, NavPers 10086-A.

PRECAUTIONS AND TECHNIQUES IN MAKING ELECTRICAL MEASUREMENTS

Most troubles can be found by taking voltage measurements. These measurements can be made easily, since they are always made between two points in a circuit and the operation of the circuit need not be interrupted. Unless otherwise indicated in the voltage chart, voltages are usually measured between the indicated points and ground.

Always use a meter that has the same ohms-per-volt sensitivity as the one used originally to develop the voltage chart. The type of reference meter used will be stated on the chart. Always begin voltage measurements by setting the voltmeter on the highest range, so that the voltmeter will not be overloaded. Then, if it is necessary to obtain increased accuracy, set the voltmeter to a lower range. Always use the range that gives a deflection on the upper part of the scale.

In checking cathode voltage, remember that a reading can be obtained when the cathode resistor is actually open, the resistance of the meter acting as a cathode resistor.

Certain precautions must be followed when measuring voltages above a few hundred volts since high voltages are dangerous and can be fatal. When it is necessary to measure high voltages, observe the following rules.

1. Connect the ground lead to the voltmeter.
2. Place one hand in your pocket.
3. If the voltage is more than 300 volts, shut off the power, connect the hot test lead, step away from the voltmeter, turn on the power, and note the reading on the voltmeter. Do not touch any part of the voltmeter, particularly when it is necessary to measure the voltage between two points both of which are above ground.

It is essential that the voltmeter resistance be at least 10 times as large as the resistance of the circuit across which the voltage is measured. If the voltmeter resistance is comparable to the circuit resistance, the voltmeter will indicate a lower voltage than the actual voltage present when the voltmeter is not in the circuit.

When a voltmeter is loading a circuit, the effect can be noted by comparing the voltage reading on two successive ranges. If the voltage readings on the two ranges do not agree, voltmeter loading is excessive. The reading (not the deflection) on the highest range will be greater than on the lowest range. If the voltmeter is loading the circuit heavily, the deflection of the pointer will remain nearly the same when the voltmeter is shifted from one range to another.

To minimize voltmeter loading in high resistance circuits, use the highest voltmeter range. Although only a small deflection will be obtained (possibly only 5 division on a 100-division scale), the accuracy of the voltage measurement will be increased. The decreased loading of the voltmeter will more than compensate for the inaccuracy which result from reading only a small deflection on the scale of the voltmeter.

Current measurements other than those indicated by the panel meters ordinarily are not required in troubleshooting. Under special circumstances where the voltage and resistance measurements alone are not sufficient to localize the trouble, a current measurement can be made by opening the circuit and connecting an ammeter in series. This procedure is not recommended except in very difficult cases.

When the meter is inserted in a circuit to measure current, it should always be inserted away from the r-f end of the resistor. For example, when measuring plate current, do not insert the meter next to the plate of a tube, but insert it next to the end of the resistor which connects to the power supply. This precaution is necessary to keep the meter from affecting r-f voltages.

CAUTION: A meter has least protection against damage when it is used to measure current. Always set the current range to the highest value. Then, if necessary, decrease the range to give a more accurate reading. Avoid working close to full-scale reading because this increases the danger of overload.

In most cases, the current to be measured flows through a resistance which is either known or can be measured with an ohmmeter. The current flowing in the circuit can be determined by dividing the voltage drop across the resistor by its resistance value. The drop across the cathode resistor is a convenient method of determining the cathode current.

Before making resistance measurements, turn off the power. An ohmmeter is essentially a low-range voltmeter and battery. If it is connected to a circuit to which power is being applied, the needle will be forced off scale and the meter movement may be burned out.

Capacitors must always be discharged before resistance measurements are made. This is very important when checking power supplies that are disconnected from their load. The discharge of the capacitor through the meter will burn out the meter movement and in some cases may endanger life.

It is important to know when to use the low resistance range of an ohmmeter. When checking circuit continuity, the ohmmeter should be set on the lowest range. If a medium or high range is used, the pointer may indicate zero ohms, although the resistance may be as high as 500 ohms. When checking high resistances or measuring the leakage resistance of capacitors or cables, the highest range should be used. If a low range is used in this case, the pointer will indicate infinite ohms, although the actual resistance may be less than a megohm.

When a resistance is measured and the value is found to be less than expected, make a careful study of the schematic to be certain that there are no resistances in parallel with the one that has been measured. Before replacing a resistor because its resistance measures too low, disconnect one terminal from the circuit and measure its resistance again to make sure that the low reading does not occur because some part of the circuit is in parallel with the resistor.

When checking a grid resistance, a false reading may be obtained if the tube is still warm and the cathode is emitting electrons. Allow the tube to cool, or connect the ohmmeter test leads so that the negative test lead is applied to the grid.

Tolerance is the normal difference to be expected between the rated value of the resistor and its actual value. Most general purpose resistors have a tolerance of 20 percent. For example, the grid resistor of a stage might have a rated value of 1 megohm. If the resistor were measured and found to have a value between 0.8 megohm and 1.2 megohms, it would be considered normal. Some precision resistors and potentiometers are used. When a resistor is used whose value must be very close to its rated value, the tolerance is stated on the diagram and in the maintenance parts list.

The ohmmeter method of checking electrolytic capacitors is a method used by many technicians if precision test equipment is not available or close at hand.

A resistance measurement is made on the discharged electrolytic capacitor, using the high-resistance range of the ohmmeter. When the ohmmeter leads are first applied across the capacitor, the meter pointer rises quickly and then drops back to indicate a high resistance. The test leads are then reversed and reapplied. The meter pointer should rise again—even higher than before—and again drop to a high value of resistance. The deflections of the meter are caused when the capacitor is charged by the battery of the ohmmeter. When the leads are reversed, the voltage in the capacitor adds to the applied voltage, resulting in a greater deflection than at first.

If the capacitor is open-circuited, no deflection will be noted. If the capacitor is short-circuited, the ohmmeter indicates zero ohms. The resistance values registered in the normal electrolytic capacitor result from the fact that there is leakage present between the electrodes. Because the electrolytic capacitor is a polarized device, the resistance will be greater in one direction than the other.

Should a capacitor indicate a short circuit, one end of it must be disconnected from the circuit and another resistance reading be made to determine if the capacitor is actually at fault.

Unless your ohmmeter has a very high resistance scale you will not see a deflection of the meter when checking small capacitors. Even a scale of R x 10,000 is not sufficient for very small ones; the smaller the capacity the less leakage across the plates, therefore more resistance.

Electron tubes do not last indefinitely. Coated cathodes lose their power to emit electrons because the coating flakes off. Likewise, impregnated emitters of filament type tubes become depleted with age. There are other factors that cause electron tubes to function improperly—for example, defective seals permit air to leak into the tube and "poison" the emitting surface, and vibration or excessive voltage may cause internal shorts or opens. Whenever electronic equipment operates subnormally one of the first maintenance procedures is to check the tubes with a tube tester. This often results in finding weak tubes and replacing them prior to failure. A new tube should be tested before it is used.

Two types of tube testers are in general use. One type, the EMISSION TYPE tester, indicates the relative value of a tube in terms of its ability to emit electrons from the cathode. The second and more accurate type is the MUTUAL-CONDUCTANCE (or transconductance) tube tester. This tube tester not only gives an indication of the electron emission but also indicates the ability of the grid voltages to control the plate current.

The end of a useful life of a tube is usually preceded by a reduction in electron emissivity—that is, the cathode no longer supplies the number of electrons necessary for proper operation of the tube. In the emission tester, the proper voltages are applied to each electrode in the tube, and a meter indicates the plate current. If the tube has an open element or is at the end of its useful life, the emission tester gives an indication of this defect in the lower, or reject, portion of the meter scale.

A tube may have normal emission and still not operate properly because tube efficiency depends on the ability of the grid voltage to control the plate current. The emission type tester indicates only the plate current and not the ability of the grid to control the plate current. The transconductance type tube tester, however, indicates how the tube operates, not merely the condition of the emitting surface.

The terms "mutual conductance" and "transconductance" are used interchangeably in many texts. The Navy Department prefers transconductance, but many commercial tube testers are marked "mutual conductance."

When the prefix "dynamic" is used, as in "dynamic transconductance," it means that the characteristics of the tube in operation are being tested. The difference between the dynamic and static characteristics lies in the effect produced by the load impedance on the operation of the tube. Most tube testers, other than the emission type, test the dynamic characteristics by placing the tube in a working circuit.

Tube Tester

The tube tester shown in figure 7-11 is a typical portable tube tester of the dynamic mutual-transconductance type designed to test electron tubes of the standard type and many of the miniature and subminiature types. A multimeter section, using the same indicator, is also incorporated in the equipment to permit measurements of a-c and d-c volts, d-c mils, and resistance and capacitance in a number of ranges.

Let us now consider each of the individual tests performed by the instrument one at a time. These tests are: (1) line voltage test, (2) short circuit test, (3) noise test, (4) rectifier test, (5) mutual-conductance test, (6) gas test, and (7) test performed by means of the multimeter section.

The tube tester has a roller chart indicating the tubes that may be tested. Listed opposite the tube designations is a series of numbers and letters which indicate the position of each switch and potentiometer of the SELECTORS and also the correct pushbutton to push. These switch positions connect the tube into a circuit that is comparable to the operating circuit of the tube. When the potentiometers are adjusted to the values indicated on the chart, the correct operating voltages are applied to the tube in order that it can be checked under operating conditions. As newer tubes than those listed on the roller chart are used in equipments, other charts are published giving the new switch

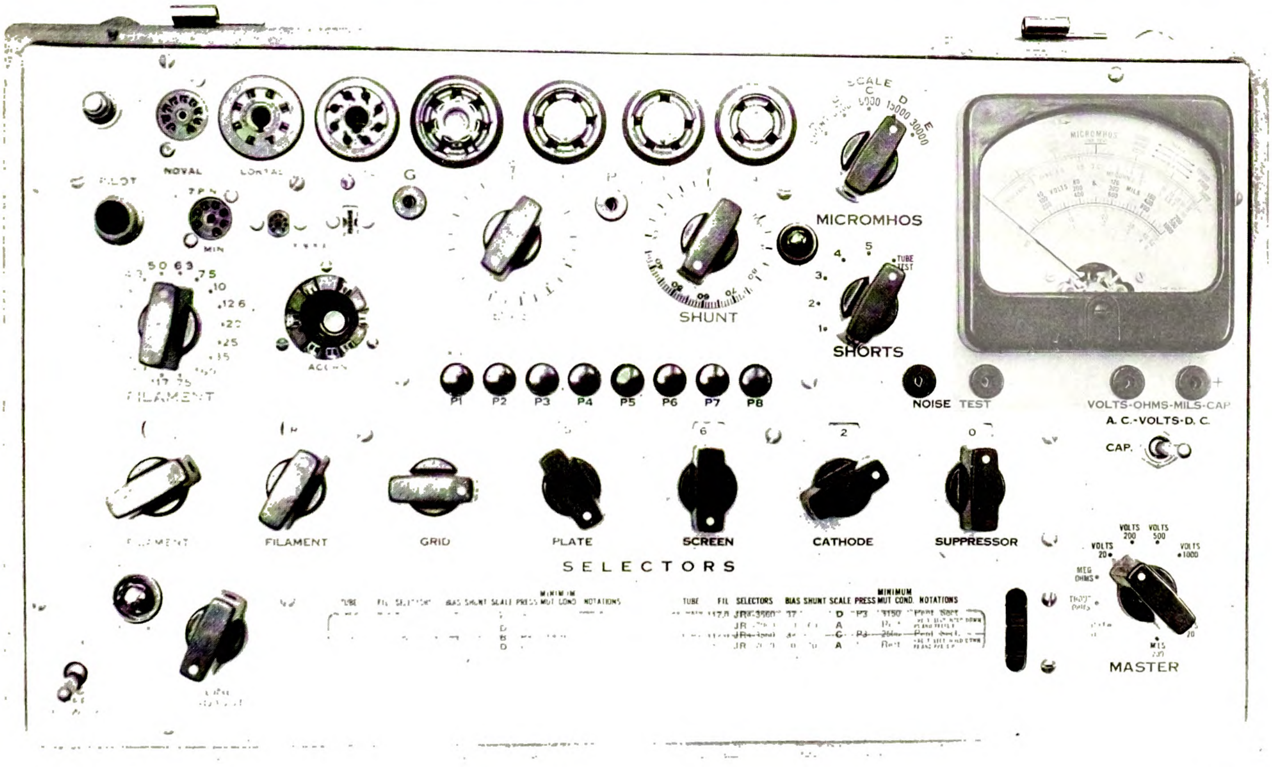

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Figure 17-11.—Typical tube tester.

positions and potentiometer settings. When conditions warrant, new roller charts incorporating the latest tubes are prepared

LINE VOLTAGE TEST.—It is necessary to maintain rated voltage across the primary of the power transformer if the meter of the tube tester is to register correctly. Therefore, a variable resistor is connected in series with the power input leads so that the voltage applied to the primary may be adjusted to the correct value. A special switch (the line-adjustment switch) connects the meter to an appropriate circuit that permits a visual determination of the correct setting of the line-adjustment control.

This line voltage should be adjusted after the filament switch is in the correct position and the tube is in the test socket. Some tubes draw a high filament current and would load down the operating voltage of the equipment if the line was adjusted first. The tube tester is designed to accurately test tubes under certain operating conditions, but these operating voltages must be accurate to accomplish this purpose. Correct line voltage adjustments will result in the required operating voltages.

SHORT CIRCUIT TEST.—The short circuit test is used to determine if there is a short between any two elements within the tube. The SHORTS switch connects the various elements of the tube under test to a voltage source in series with a neon lamp so that it glows if there is a short between the elements.

NOISE TEST.—The noise test is similar to the short circuit test and is used to check for any intermittent disturbances that are too brief to be detected on the neon lamp. Two test leads are connected into the jacks above and below the neon lamp (across the neon lamp) and the other ends of the leads are connected to the antenna and ground of a radio receiver. The SHORTS switch is then turned through the various positions as the tube under test is tapped gently. Any intermittent disturbances between the electrodes cause a momentary oscillation that is reproduced by the loudspeaker as noise.

RECTIFIER TEST.—Rectifier tubes and diode detector tubes can be tested only for emission; therefore, the rectifier test is quite simple. The diode or rectifier tubes are tested by first setting all the switches and potentiometers to the positions indicated on the roller chart. The tube is placed in the proper socket and the line voltage is adjusted after the tube has been allowed time to warm up. Then the designated diode or rectifier button is pushed. The meter will indicate above the rectifier mark for a good tube. If the reading is below the mark the tube is weak or gassy. If there are two or more plates in the tube each is tested separately.

MUTUAL-CONDUCTANCE TEST.—Mutual-conductance tests are performed on amplifier tubes by positioning the SELECTOR switches and potentiometers as indicated by the roller chart. After placing the tube in the proper socket, and adjusting the line voltage, a short circuit test should be conducted. To make the mutual-conductance test, the designated push-button is depressed. The meter will indicate the quality of the tube. It should be noted that to obtain accurate indications on the meter, the RANGE switch must be in the correct position. A reading lower than that given on the roller chart indicates a weak tube. A higher reading may indicate a gassy tube.

GAS TEST.—This test is used to determine whether or not there is gas present in the vacuumized envelope of the tube. It should be noted that this is NOT a test for gas-filled tubes such as thyratrons. The gas test is usually made after the quality test and therefore the switches and potentiometers are in the required positions. The GAS NO.1 button is depressed, which connects the proper grid and plate voltages. This will result in a certain indication on the meter. While GAS NO. 1 button is held down, GAS NO. 2 button is also depressed. If the tube is gassy, the meter reading will increase. If the increase is more than two divisions on the scale, the tube is not acceptable due to excessive gas.

Tube Tester Limitations

In general, tube testers do not completely indicate tube performance because they present a fixed impedance to the tube grid and plate which may or may not be that of the equipment in which the tube is to operate. Also, the tester takes no account of the interelectrode capacity of the tube which makes an accurate prediction of tube performance with a tube tester difficult. The range of operating frequency affects performance also.

It is impracticable to design a complete testing instrument that will evaluate the performance of any tube in any circuit in which it is being used. A tube may test low on the tester and yet work perfectly well in the circuit or, on the other hand, it may check good in the tester and not function in the equipment. As a rule, therefore, only dead, shorted, or extremely weak tubes should be discarded purely on the basis of a tube tester check.

Further, it is NOT advisable to replace a large number of tubes at one time. It is better to replace them either tube by tube or in small groups. Be sure to replace each tube with an identical replacement.

Another aid to checking new tubes is the "eyeball" check. Many new electron tubes with visible defects find their way into equipment. A quick visual inspection of all new tubes will save time by eliminating these obvious defects. Some of the things to watch for are: crushed spacers, loose internal plate structures, bent or missing pins, broken tips and cracked-glass envelopes.

CATHODE-RAY OSCILLOSCOPE

The cathode-ray oscilloscope is one of the most useful and versatile of test instruments. It is essentially a device for displaying graphs of rapidly changing voltages or currents, but is also capable of giving information concerning frequency values, phase differences, and voltage amplitude. It is used to trace signals through electronic circuits to localize sources of distortion and to isolate troubles to particular stages.

The oscilloscope is an instrument consisting of a cathode-ray tube and associated circuits for use in viewing wave shapes of voltages or currents. The cathode-ray tube, which is discussed in detail in Basic Electronics, NavPers 10087-A, consists of three parts—an electron gun for supplying a stream of electrons in the form of a beam, deflection plates for changing the direction of the electron beam a small amount, and a screen covered with a material which gives off light when struck by the stream of electrons directed at it by the gun.

As shown in figure 17-12 the associated circuits include a time-base (sweep) generator whose output is amplified by the horizontal amplifier. This output is applied to the horizontal deflection plates, causing the electron beam to move from the left to the right side of the screen at a uniform rate. Then the beam returns hurriedly to the left side where it begins another sweep across the screen. This

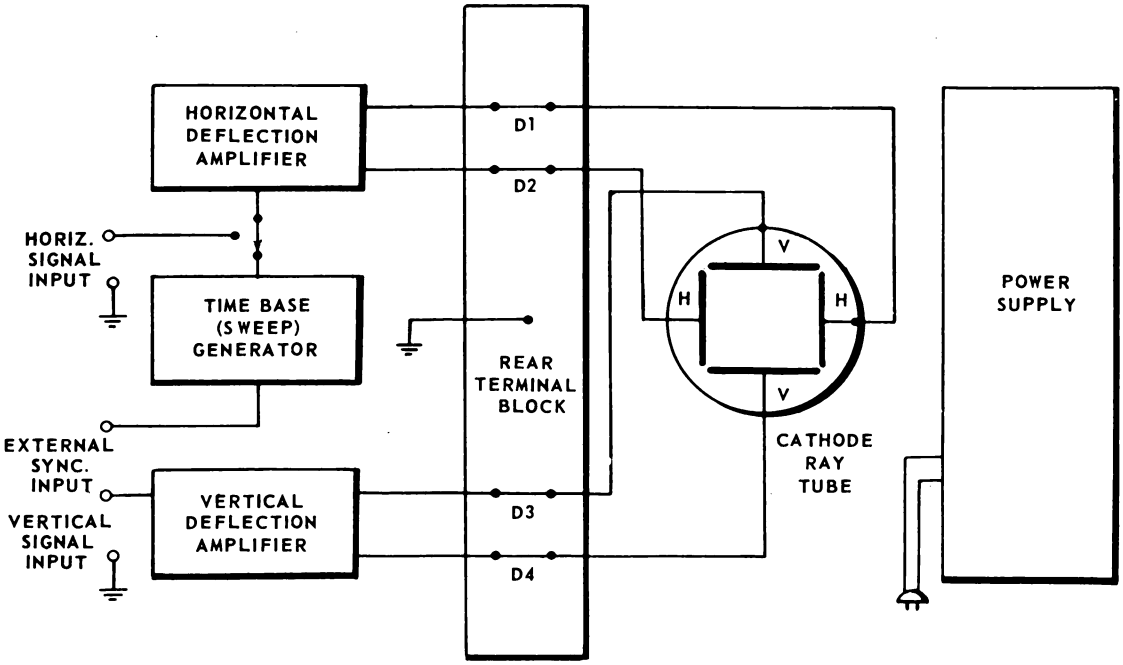

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Figure 17-12.—Block diagram of a cathode-ray oscilloscope.

action is accomplished by generating a voltage that rises at a uniform rate to a certain value and then quickly drops to its starting value. A waveshape such as this is called a sawtooth wave.

A sawtooth voltage wave is applied to the horizontal deflection plates, where it causes the electron stream to change direction. Since negative voltages repel and positive voltages attract electrons, the gradual rise in voltages causes the left plate to become increasingly negative and the right plate increasingly positive, and thereby causes the spot to move across the screen. The quick drop of the voltage to its starting value returns the spot from right to left in a very short time. This is called the flyback time.

The sawtooth voltage is normally generated by the time-base generator, and applied to the horizontal deflection amplifier. Should some other external voltage for horizontal deflection be desired, it is applied to the terminals marked horizontal signal input. The waveform fed to the horizontal deflection amplifier is increased in amplitude to that needed for a trace of the desired length and applied to the horizontal deflection plates.

Signals applied to the vertical signal input terminals are amplified by the vertical deflection amplifier and applied to the vertical deflection plates.

By studying figure 17-13, you can see how a sine wave is reproduced on the screen when a sawtooth voltage is applied to the horizontal plates and a sine wave voltage is applied to the vertical plates. The sawtooth, which represents time, is divided into segments numbered t_0, to t_4. The input sine wave also has the same divisions to show the instantaneous voltage amplitude at these same points. The resultant is a single cycle of sine wave on the screen.

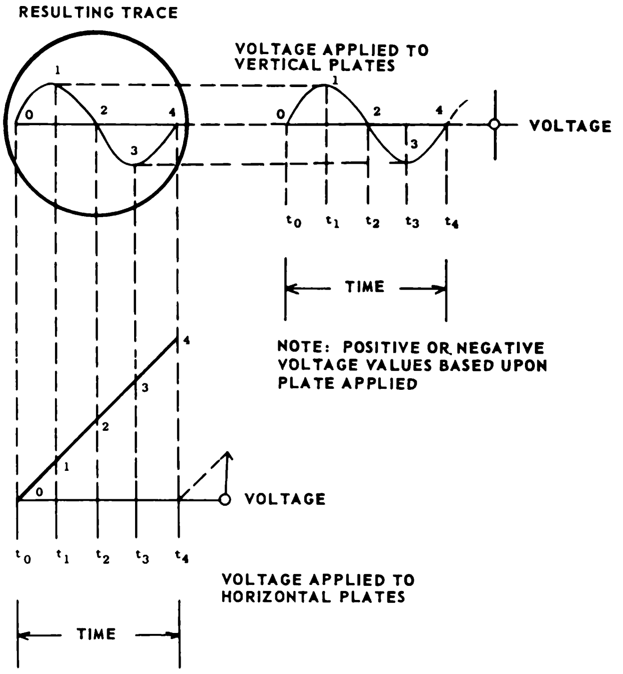
Your ability to properly operate an oscilloscope will not only help you perform your duties as an FT, but will provide a means of visually illustrating the operation of various electrical circuits to be studied as you advance in rate.

A typical cathode-ray oscilloscope is shown in figure 17-14. A description of the operating controls and their function is as follows:

FRONT PANEL CONTROLS:

INT-OFF—operates the power OFF-ON switch and controls the intensity or brightness of the image on the screen.

FOCUS—adjusts the focus or sharpness of the trace on the cathode-ray tube.


RESULTING TRACE
VOLTAGE APPLIED TO VERTICAL PLATES
0
1
2
3
4
VOLTAGE
t_0
t_1
t_2
t_3
t_4
TIME
VOLTAGE
VOLTAGE APPLIED TO HORIZONTAL PLATES
TIME

NOTE: POSITIVE OR NEGATIVE VOLTAGE VALUES BASED UPON PLATE APPLIED

12.258

Figure 17-13.—Development of sine wave on face of oscilloscope.

HOR. and VERT. POS. (left-right, down-up)—used to adjust the position of the trace on the screen, either horizontally or vertically.

HORIZONTAL AMP. PANEL:

HOR. ATTEN.—selects the source of signal, a-c with attenuation sweep, or d-c. The signal is then fed to the horizontal amplifier.

HOR. GAIN—controls the gain of the horizontal amplifier.

DC—connection for d-c input to the horizontal amplifier.

AC—connection for a-c input to the horizontal amplifier.

GND—connection for ground when using either a-c or d-c inputs to the horizontal amplifier.

SWEEP CIRCUIT OSC. PANEL:

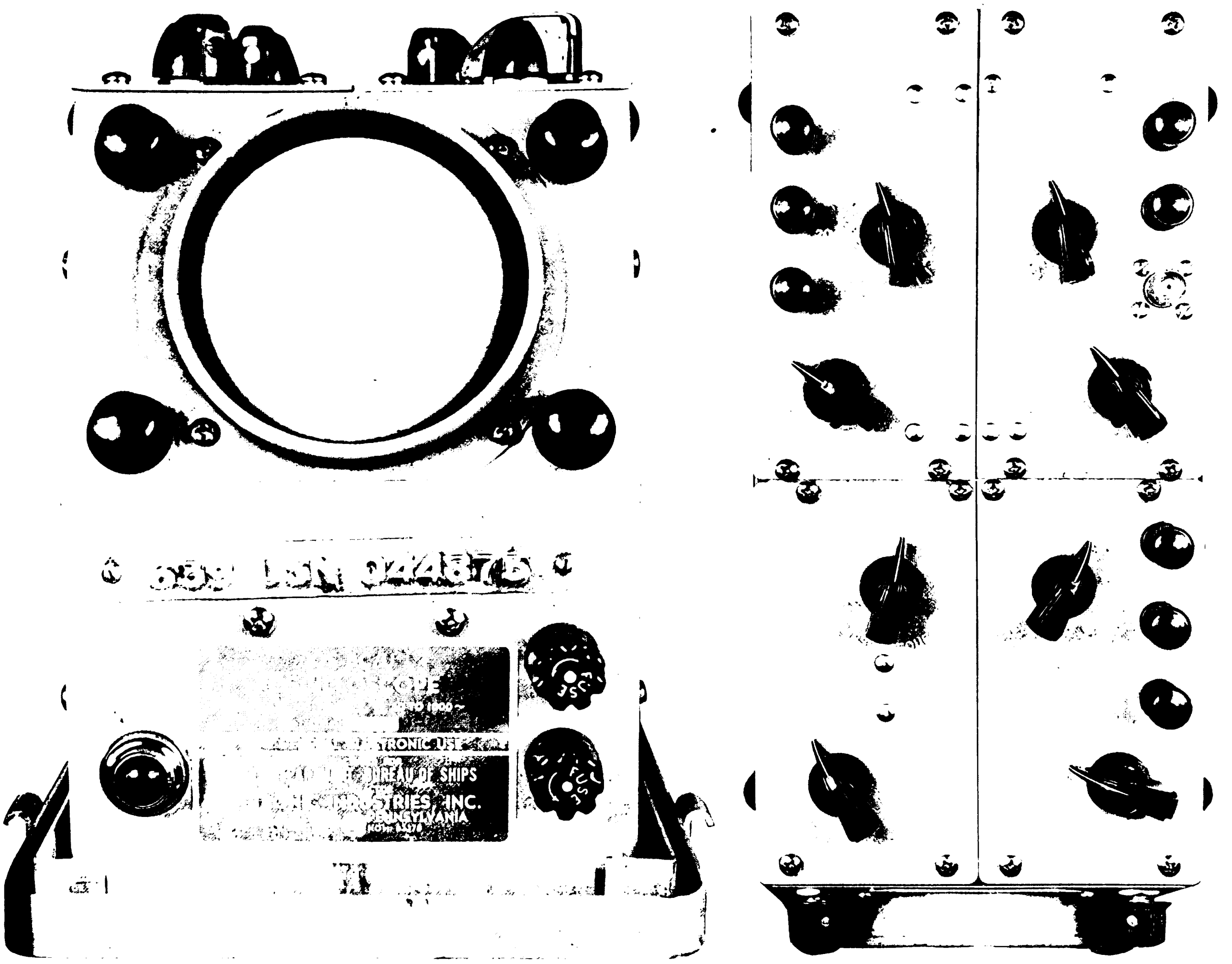
COARSE FREQUENCY—provides a coarse adjustment of the sweep frequency.

VERNIER FREQUENCY—provides a fine or jernier adjustment of the sweep frequency.

SYNC. CIRCUIT PANEL:

SYNC. SELECTOR—provides for the selection of the synchronizing voltage source as follows:

LINE—signal is taken from input to power supply.



1.86A

Figure 17-14.—General-purpose oscilloscope OS-8c/u.

EXT.—signal is supplied by an external source connected to the EXT. terminal.

INT.—signal is taken from the input to the vertical amplifier.

LOCKING—selects the polarity and amplitude of the synchronizing voltage applied to the sweep circuit oscillator.

EXT.—input for external synchronizing voltage.

Z AXIS—connection for external voltage to be used in intensity modulation of the electron beam.

LINE—an external source of line supply frequency.

VERTICAL AMP. PANEL:

VERT. ATTEN.—provides for attenuation of a-c signals or d-c input without attenuation.

VERT. GAIN—controls the gain of the vertical amplifier.

DC—connection for d-c input to the vertical amplifier.

AC—connection for a-c input to the vertical amplifier.

GND—connection for ground when using either a-c or d-c inputs to the vertical amplifier.

OPERATION.—The operation of OS-8C/U cathode-ray oscilloscope for observation of waveforms is relatively easy, in that the signal to be observed is applied to the a-c terminal of the vertical amplifier and that the horizontal sweep frequency need only be synchronized with it. The steps for operating the 0S-8C/U are listed below.

1. The signal to be observed is connected to the a-c input terminal of the vertical amplifier, and the ground connection of the input signal is connected to the GND terminal.

2. The INT-OFF control is turned clockwise to switch the power on. After the oscilloscope has warmed up, adjust the brightness or intensity of the trace to a comfortable level.

3. Set the COARSE FREQUENCY control to the lowest frequency.

4. Set the SYNC. SELECTOR switch to the INT. position.

5. Set the VERT. GAIN and the VERT. ATTEN. controls for suitable deflection.

6. Set the HOR. GAIN control for desired pattern width.

7. Slowly rotate the VERNIER FREQUENCY control until the desired pattern appears and is steady.

8. If the number of cycles is too great, the COARSE FREQUENCY control is adjusted a step higher until the desired number of cycles appear and are steady. This may require readjustment of the VERNIER FREQUENCY control.

9. The trace can then be locked in synchronization by adjusting the LOCKING control, either positive or negative, until the pattern appears steady and fixed.

When it is desired to use an external synchronizing voltage, it can be connected into the EXT. synchronization terminal. The SYNC SELECTOR must be turned to EXT. The other controls are adjusted as above. When it is desired to use line voltage for synchronization, the SYNC. SELECTOR is turned to LINE and the other controls are adjusted as above.

TROUBLESHOOTING

A large part of your daily activities will be spent in preventing equipment failure by detecting defective operation and component deterioration in the early stages. This is accomplished by properly carrying out the Planned Maintenance System. Nevertheless, components do break down even under ideal conditions and you will have to trouble-shoot to find and correct the casualty or malfunction caused by faulty components.

In this section we will describe the troubleshooting procedure which is followed by most experienced technicians in locating all except the most self-evident faults. It consists in starting with large areas (circuits or parts of a circuit) suggested by the symptoms and eliminating those areas where the fault is NOT located. When the general area containing the fault is identified, progressively smaller segments are eliminated until only the small segment containing the fault is left. When this stage is reached, the fault usually reveals itself; if not, it can be located by individually testing a small number of parts and connections. Logical troubleshooting by a process of elimination can be applied to all types of fire control equipment.

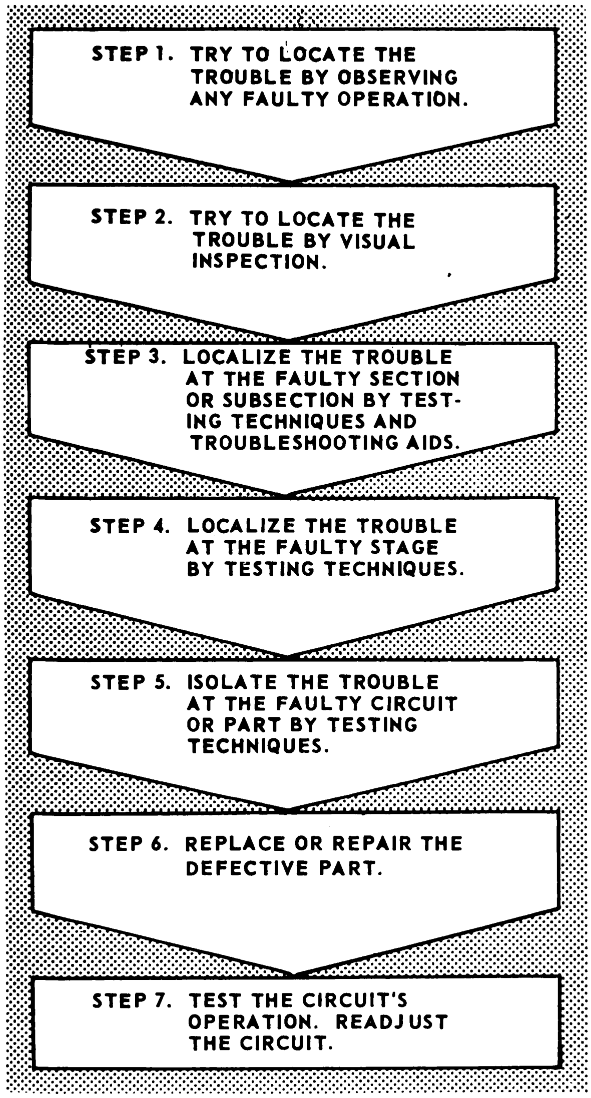
TROUBLESHOOTING PROCEDURE

The following procedure is general enough to be useful when troubleshooting most equipments. Figure 17-15 shows in block form the seven steps required to analyze the equipment, find the defective component, and make the appropriate repairs.

STEP 1. Investigate the symptoms. Try to locate the trouble by observing the equipment's operation. Check the operator's impressions of what happened at the time of failure. Look for any telltale evidence that will reveal the major unit in which the trouble exists. If you know the equipment well you can generally tell in what functional circuit the fault exists by observing the operation of the equipment and meter or scope indications. This first step is the beginning of the process of casualty analysis using effect-to-cause reasoning. You see the effect (symptoms); now you must analyze the evidence to find the cause of trouble.

STEP 2. An internal visual check provides the logical second step in arriving at a defective component. Look for loose connections, burned parts, controls which are not working properly, resistors which are discolored, tubes without glowing filaments, or any other abnormal indications. Many casualties do not result in symptoms which can be detected directly by our senses so it is necessary to resort to other means of detecting failures. The next steps require the use of test equipment.

STEPS 3, 4, and 5. Troubleshooting steps 3, 4, and 5 consist of localizing the trouble to the faulty part. If the trouble has not resolved itself from a logical solution of the data available in steps 1 and 2, you must then utilize the troubleshooting aids discussed later in this section. In conjunction with the troubleshooting aids and logical reasoning, tracing a signal from its source through a circuit is the best technique for isolating the trouble to a section, stage, or part. The signal can be traced from


STEP 1. TRY TO LOCATE THE TROUBLE BY OBSERVING ANY FAULTY OPERATION.
STEP 2. TRY TO LOCATE THE TROUBLE BY VISUAL INSPECTION.
STEP 3. LOCALIZE THE TROUBLE AT THE FAULTY SECTION OR SUBSECTION BY TESTING TECHNIQUES AND TROUBLESHOOTING AIDS.
STEP 4. LOCALIZE THE TROUBLE AT THE FAULTY STAGE BY TESTING TECHNIQUES.
STEP 5. ISOLATE THE TROUBLE AT THE FAULTY CIRCUIT OR PART BY TESTING TECHNIQUES.
STEP 6. REPLACE OR REPAIR THE DEFECTIVE PART.
STEP 7. TEST THE CIRCUIT'S OPERATION. READJUST THE CIRCUIT.

12.259

Figure 17-15.—Typical troubleshooting procedures.

the source until it is lost at some checkpoint, or you can start at the output of the circuit and work backward until you find the defective stage. To find the defective part is a matter of checking a small number of elements.

STEP 6. This entails the replacement or repair of the defective part. You know that ALL replacements or repairs should duplicate the defective part.

STEP 7. Test the circuit and equipment operation. Readjust the circuit if necessary. After you make the repairs, always test the equipment. Use the operational tests given in the applicable OP or log. They contain information telling you what adjustments are required and how to make them.

SYSTEM TROUBLESHOOTING AIDS

Basically the purpose of corrective maintenance is to restore the system's operation to acceptable standards. To restore the system to its operational standard, the operation and the standards of the system must be known. Firsthand knowledge of the system's operation can be obtained by performing the tests and the preventive maintenance called for in the PMS. The system's OPs contain detailed information on the system's operation as well as the functions of the major units in the system. We will discuss some of the maintenance orientated diagrams supplied to assist you in troubleshooting the weapon system as a unit.

One-Function Schematic Diagram

These drawings show the internal and interconnecting circuitry between all parts of the weapon system. They depict in a single diagram all circuits involved in one particular function (quantity or signal) of a system. This eliminates the need for using many separate diagrams for each of the equipments involved in the particular function. Circuit information is displayed by functional flow from left to right. The unit in which the signal originates is on the left of the drawing, the unit that ultimately receives the signal is to the right. All major equipments, terminal boards, patch panels, dials, plugs, and other electrical components are labeled.

These one-function diagrams are not only an aid in troubleshooting but they provide a key to the understanding of the entire weapon system.

Data Functional Diagrams

These diagrams show data transmission and functional circuits relevant to weapon system loops or modes of operations. Primary data flow is depicted as heavy lines. Each diagram emphasizes all alternate and test inputs and all points of data readout such as servodials, test points, and scope indications for a particular loop or mode. By tracing the primary data flow lines you can quickly determine which components are significant to fault isolation and functional understanding.

Control Functional Diagrams

These diagrams are provided only for the more complex control circuits. The diagrams show the time related, ON-OFF stages of lamps, relays, switches, and other control devices for the various control circuits, with primary data flow depicted as heavy lines. Use of these diagrams will enable you to quickly determine the desired ON-OFF stage of the various control or control related devices. A comparison with the actual circuit indications will isolate a fault to specific fuctional areas or to components in the control circuit.

Fault Directories

In the PMS, tests are keyed to the troubleshooting procedures. The fault directories are the primary means of determining the appropriate troubleshooting aids for an indication of a fault observed in the system tests. Each fault directory lists the various phases of the associated test in corresponding sequence, with the probable faults which may occur during each phase of the test. References to the most appropriate troubleshooting documents associated with each test indication are provided by the directory. In most cases, the referenced documents are functional diagrams and fault logic diagrams.

The Indictor Directory is the primary means of determining the appropriate troubleshooting documents for an indication of a fault observed on a specific indicator during random operation of the system. This directory provides an alphabetical listing of all indicators shown in the functional diagrams. The listing references the most appropriate diagrams associated with each indicator.

Fault Logic Diagrams

These diagrams will enable you to rapidly isolate faults encountered in system tests. Each diagram begins with a statement describing the fault. The first block in the diagram contains a question about the fault that may be answered either "yes" or "no". If the answer is yes, you proceed to the next block via the solid line; if the answer is no, you would follow the broken line leaving the box. The second block contains a yes or no question similar to the one in the first block. You again determine the proper answer to the question and proceed to the next block according to the answer obtained. This process is repeated until you are referred to a block containing a statement describing the action required to correct the fault.

Indications that occur normally during the system tests and which can be helpful in fault analysis are presented in the diagrams as questions. Blocks that contain fault correction procedures reference functional diagrams, further troubleshooting procedures, or the fault-troubleshooting documentation reference table associated with each fault logic diagram.

EQUIPMENT TROUBLESHOOTING AIDS

Servicing Block Diagrams

This troubleshooting aid should enable the technician to see, in a general way, the course of each circuit. From it you can perceive the relationship between circuits and components. Also, you can determine the general location of the test points for checking the condition of the equipment. The servicing block diagram should aid you in localizing the trouble to a small segment.

Schematic Diagrams

A schematic diagram shows how the parts of a circuit are connected for the operation of the equipment. It does not tell how the parts look or how they are constructed. Each component is illustrated by a symbol. A set of schematics enables the technician to trace the passage of energy throughout the entire equipment. The detail of each circuit is drawn. This enables the technician to determine, by test, the operating condition of each part and connection.

Voltage Distribution Diagrams

These diagrams trace the distribution of the supply voltages throughout the equipment. The diagrams show all the relays, contacts, switches, and access points for that particular voltage distribution.

Voltage and Resistance Charts

These charts show the normal voltage and resistance values at the pins of connectors and tube sockets. Voltage and resistance charts are used to pinpoint the faulty element after it has been isolated through the use of troubleshooting charts and servicing diagrams. After isolating the source of trouble to a stage or area of a circuit, determine which chart you should use. Generally, there is one for each chassis in the equipment. Using servicing diagrams for reference, check voltage in the circuit starting with the input stage and continuing until the output is reached. Repeat this procedure for resistance measurements. When an abnormal indication is observed, discontinue the procedure and check the component or components involved to pinpoint the trouble. However, keep in mind that various controls will affect voltage and resistance readings: if a faulty reading is obtained, these controls should be checked for their proper setting.

Equipment Troubleshooting Pyramids

These pyramids deal with the interdependency of the subassemblies essential to each function of a piece of equipment. The pyramid starts with an output function and, for a given local test setup, lists the values and allowable tolerances of that function. Subsequent checks of the various inputs that affect the function are contained in blocks which radiate downward from the statement of the function. The blocks contain recommended correction action if the check of the input is at fault. Each leg of the pyramid is terminated by an input and reference to other pyramids or related documents, or by a source assembly such as an oscillator. Thus, the equipment troubleshooting pyramids will enable you to quickly localize faults and to perform the necessary corrective action by referencing the associated material.

Troubleshooting Printed Circuits

Locating components and circuit tracing in a printed circuit is generally easier than that experienced with wired circuits. The mass of wiring, terminal strips, and obscured test points are virtually eliminated. The components in a printed circuit are grouped in an orderly manner and tracing the circuit is somewhat like following a breadboard model.

SERVICING TRANSISTOR CIRCUITS

After you have worked with vacuum tube equipment, you will find that maintaining and troubleshooting transistorized equipment presents no new problems. Most transistorized equipments use printed circuits, on which components are neatly arranged without stacking. This makes the transistors, resistors, capacitors, and other components easy to get at for troubleshooting. However, you must be careful to prevent damage to the printed wiring while you are investigating with test probes.

One of the outstanding advantages of transistors is their reliability. Over 90 percent of the failures in electron tube equipment are tube failures. Transistors, however, have long life. This factor, among others, decreases the amount of maintenance necessary to keep transistorized equipment operating.

TRANSISTOR SERVICING TECHNIQUES

The techniques used in servicing transistorized equipment are similar to those used in servicing electron tube circuits. Basically, these techniques are:

1. Power supply check
2. Visual inspection
3. Transistor check
4. Voltage check
5. Resistance check
6. Signal tracing
7. Component substitution

POWER SUPPLY CHECK.—The first step you should take in troubleshooting is to check the power supply to see if its output voltages are present, and are set at their correct value. Improper supply voltages can cause odd effects. You can prevent many headaches if you first check the power supply.

VISUAL INSPECTION.—Visual inspection is a good servicing technique. Occasionally you can find a loose wire or faulty connection before extensive voltage checks are made. Faulty components such as burned resistors seldom occur, since the power supply voltage is usually very low compared to a vacuum tube power supply.

TRANSISTOR CHECK.—Transistors, like electron tubes, can be checked by substitution. Transistors, however, have a characteristic known as leakage current which may affect the results obtained when the substitution method is used. The leakage current can affect the gain or amplification factor of the transistor. It is more critical in certain applications than in others. Thus, it is possible that a particular transistor will operate satisfactorily in one circuit and not in another. It also has been found that the amount of leakage current will increase slightly as the transistor ages.

TRANSISTOR CHECKER.—Transistors can be checked by using a Transistor Tester. The following tests will reveal the condition of a transistor.

1. Tests to determine if its elements (emitter, base, collector) are short circuited.
2. A test to determine the current gain.

One type of transistor tester used by technicians is the TS-1100/U. It can measure current gain while the transistor under test is either in or out of circuit. But the transistor must be removed from the circuit when you are checking for a short-circuited condition.

VOLTAGE CHECKS.—Voltage measurements provide a means of checking circuit conditions in transistor circuits as they do in tube circuits. The voltages in transistor circuits are much lower than in tube circuits. For example, the bias voltage between the base and emitter is in the order of 0.05 to 0.2 volts. Therefore, a sensitive VTVM is usually required. When you make voltage checks make sure polarity is observed to avoid error in measurements. In an electron tube circuit, if you find a positive voltage on a grid, a leaky coupling capacitor is indicated. But in a transistor circuit the base to emitter voltage may be positive or negative, depending on the type of transistor. For example, the PNP type normally operates with the base negative with respect to the emitter, whereas the opposite is true of NPN transistors. Check the shematic of the circuit under test for the proper polarity as well as magnitude of voltage.

There may be time when you will want to make a current check in a circuit. In circuits that are wired in the conventional manner you can easily unsolder a lead or remove a connection, and then place an ammeter in the circuit. With printed wiring this is not always possible. But you can calculate the current by using Ohm's law. For example, if the collector current is to be measured, measure the voltage drop across the collector resistor (load) and measure the resistor with an ohmmeter. By using Ohm's law, you can calculate the collector current.

RESISTANCE CHECKS.—Resistance measurements are not generally made in transistor circuits, except to check for open windings in transformers and coils. Resistors and transistors have little tendency to burn up or change value, because of the low voltage power supplies used in transistor circuits. It is important to remember that before you attempt to measure the resistance of any transistor circuit component, you must REMOVE THE TRANSISTOR OR COMPONENT. Since the ohmmeter has a battery, the wrong voltage polarity may be applied to a critical stage and cause permanent damage to the transistor. Another word of caution. Always disconnect the supply voltage before you remove a transistor from its socket. This prevents current surges that might damage the transistor.

SIGNAL TRACING AND COMPONENT SUBSTITUTION.—You can trace a signal through a transistor circuit just as you do in a vacuum tube circuit. When you find a faulty component, replace it with a duplicate.

PRECAUTIONS

Although transistors are rugged, you must observe certain precautions. The leads are the most fragile part. Whether they are long and flexible or short and rigid, they should be treated carefully. When transistors with long flexible leads are soldered or resoldered, make sure you don't overheat the transistor. Use the heat-sink technique previously described. Transistors with short rigid leads are usually plugged into sockets. In some cases, however, these transistors are plugged directly into the printed board; and then dip soldered.

Transistors require low operating voltages. Small changes in these voltages can greatly upset the biasing of transistors. In some circuits, small bias changes can result in destruction of the transistor. Therefore, make sure you don't short out any circuit components. This action could disturb all the voltage relationships in the equipment, and thus destroy a number of transistors.

Except for the special precautions and servicing techniques mentioned here, servicing transistor equipment should present no greater problem than servicing their electron tube counterparts.

SAFETY PRECAUTIONS

Much material has been written on the subject of safety precautions. Consequently, the number of accidents which occur in the Navy is small. Most of the safety precautions applicable to Fire Control Technicians are published in the OPs on the weapon system and on fire control equipment, and in Bureau of Ships Technicial Manual, NavShips 250,000 (electrical and electronic safety precautions are contained in chapter 9670). It is up to you to familiarize yourself thoroughly with these publications. Many of the safety regulations included in these manuals are the result of actual experience, so give them every possible consideration.

CAUSES OF ACCIDENTS

There are four closely related causes of accidents: CARELESSNESS, INEXPERIENCE, OVERCONFIDENCE, and FATIGUE.

CARELESSNESS is something most human beings have to overcome. You have to cultivate good working habits—you must learn to coordinate your mental and physical actions to a point where you can concentrate on the important parts of the job at hand without having to worry about the minor mechanical functions pertaining to it.

INEXPERIENCE can be the cause of accidents regardless of how careful the individual intends to be. The best solution to this problem is NEVER GUESS—you must learn to ask questions about things you are unfamiliar with or are not completely sure about. Beginners have a tendency to be overeager and desire to put their hands to work. Eagerness is a good trait in any person, but you must realize that men with more experience usually know best. Work into a job gradually and be particular about thoroughness; always be conscious of correct procedures in doing things. Train your mind and hands to function correctly so as to protect yourself and others from physical injury. For example, when you work with a screwdriver, be sure that your left hand (or right hand, if you are left-handed) is clear of the screwdriver bit, otherwise a slip of the screwdriver may drive the bit completely through your hand or may gouge deep into your arm. If you practice correct methods from the start, they'll become automatic before you realize it.

OVERCONFIDENCE can come to both young and old, experienced and inexperienced; however, it is usually more closely associated with inexperience. Often, however, men grow overconfident when they become thoroughly familiar with a particular job, and have a tendency toward carelessness. To put it briefly, always be confident that you know a job, but beware of overconfidence because it may invite mistakes which can cause accidents.

FATIGUE has always been the cause of a large percentage of accidents. You might be highly efficient when you have energy to burn, but it's another story when you get tired; your physical actions slow up and become inaccurate. Always prepare yourself for the task ahead by learning how much endurance it requires, and then get the necessary sleep, recreation, food, and exercise to keep on your toes. Remember, to be alert and to feel your best is extremely important on the job, and you can only enjoy this feeling by keeping yourself in good physical condition.

GENERAL SAFETY PRECAUTIONS

Although many specific safety precautions are laid down for you in the three main publications that cover safety, there are a few general precautions which you should remember. Let's start by discussing the handling of handtools and power tools.

Handling Tools and Machinery

Many accidents occur because of the improper handling of tools. In general, these accidents occur in the form of physical injury to the person operating the tools. The following list gives the more important general precautions to follow:

1. Whenever chipping, buffing, or grinding with handtools and power tools, always wear goggles as a protection to the eyes. Little chips from a spinning grind wheel, or a bristle from a revolving wire brush can easily put out an eye. Many of these machines are provided with a guard: be sure to use it.
2. Always ground the provided ground lead located at the plug of portable tools such as electric drills to protect yourself from shock in case a ground occurs within the tool.
3. When working with sharp handtools, always work so that the tool is moved or thrust away from the body.

4. Never wear loose clothing or a neckerchief when working with rotating tools or machinery. Such clothing may become caught in the spinning parts and drag you bodily into the machine causing severe physical injury.

5. Never use metal handtools on energized electrical equipment or circuits because you may get shocked, or the tool may cause a short circuit causing molten copper to be blown into your face and eyes.

6. Never use handtools around running machinery, nor perform adjustments to running machinery unless absolutely necessary.

7. Never lay handtools on top of running machinery where vibration may cause the tool to fall into exposed working parts.

8. In the event it is necessary to work on electric equipment while in an energized state, wear rubber gloves and use tools with insulated handles, and stand on an insulated mat. Always work with one hand in order to prevent the possibility of a circuit through your body from arm to arm.

9. When working with tools, always work in a physically comfortable position, and keep the weight of your body well centered.

Electrical Work

The following list is in addition to those precautions on handtools and machinery, and is applicable to all electrical work. This list will help you prevent electric shock or burns during daily work.

1. Do not block high voltage protective cutout on doors or covers to keep the circuit energized with the cover off. It is intended that work be performed on such electrical equipment while the circuit is deenergized.

2. Always ground the provided ground load located at the plug of portable tools such as electric drills to protect yourself from shock in case a ground occurs within the tool.

3. Always be sure that all condensers are fully discharged before commencing work on a deenergized high voltage circuit. Use an insulated shorting bar for this purpose.

4. Tag the switch OPEN (open the switch and place a tag on it stating "This circuit was ordered open for repairs and shall not be closed except by direct order of ________.") at the switchboard supplying power to the circuit on which you wish to work. When possible, remove the fuses protecting the circuit and place them in your tool box for safekeeping until the job is complete.

5. Always remove fuses with fuse pliers, and never remove fuses until after opening the switch connecting the circuit to the source of supply. Never replace a fuse with one LARGER than the circuit is designed to take.

6. Utmost precaution should be observed when inspecting behind an open-back switchboard in an energized state.

7. Never use an incandescent test lamp unless its voltage rating is greater than the highest voltage which may be tested.

8. Always test a supposedly deenergized circuit with a voltage tester before commencing work on the circuit.

9. Never work on an electric circuit or network without first thoroughly acquainting yourself with its arrangement and with its points of power feed.

Common Safety Features in Electronic Equipment

You should be aware of the safety features that are generally included in electronic equipment. Some of the common safety features are interlock switches, bleeder resistors, current-limiting resistors, insulating controls, and powerline safety devices such as fuses. Keep in mind that these features cannot always be counted on to function. Don't develop a false sense of security just because an equipment has safety features.

OPERATING FIRE CONTROL EQUIPMENT

Let us repeat—you should acquaint yourself thoroughly with the safety regulations provided in the Bureau of Weapons Ops and with those regulations posted aboard ship, before operating fire control equipment. You will be taught how to apply many of these precautions while you are learning to operate fire control instruments. The following list of general precautions will assist you.

1. Always inspect all training and elevating areas to make certain that all persons are clear, and that the areas are free of obstructions before operating directors, turrets, guns, or missile launchers.

2. Always use warning bells before training or elevating gun mounts, turrets, or launchers during routine work and practices.

3. Before leaving directors, turrets, guns, or launchers always train and elevate them to their securing positions; place all controls in the inoperative position, and deenergize all power supplied to them.

4. Slew directors and guns only when it is necessary during practices.

5. All telephone stations should be manned when operating systems automatically or remotely.

6. Notify all operators and persons concerned before shifting a system to automatic control from local control.

7. Never operate directors, turrets, or guns in automatic without having the regular operators posted at their stations.

8. Do not hesitate to stop any person from operating fire control equipment if he may cause a casualty to himself, the equipment, or to any other person.

APPENDIX I

TRAINING FILM LIST

Certain training films that are directly related to the information presented in this training course are listed below under appropriate chapter numbers and titles. Unless otherwise specified, all films listed are black and white with sound, and are unclassified. For a description of these and other training films that may be of interest, see the *United States Navy Film Catalog*, NavPers 10000 (revised).

CHAPTER 2

The Gun Fire Control Problem

MA-6886	*Fundamentals of Ballistics.* (19 min.—1949.)
SN-3193A	*Elements of a Surface Fire Control System—Part 1.* (15 min.—1944.)
SN-3193B	*Elements of a Surface Fire Control System—Part 2.* (25 min.—1944.)
SN-3193C	*Elements of an Antiaircraft Fire Control System—Part 1.* (21 min.—1944.)
SN-3193D	*Elements of an Antiaircraft Fire Control System—Part 2.* (17 min.—1944.)
MN-8633	*Effects of Roll and Pitch on Gun Train and Gun Elevation Rates.* (12 min.—Color—Sound—Unclassified—1958.)

CHAPTER 3

The Guided Missiles

MN-9161B	*Guided Missiles—Theory of Operation.* (20 min.—1950.)

CHAPTER 4

The Guided Missile Fire Control Problem

MN-8136	*Terrier, The New Fleet Weapon.* (20 min.—Color—Sound—Unclassified—1954.)
MN-8848	*Missiles of the Navy.* (19 min.—Color—Sound—Unclassified—1958.)

CHAPTER 5

Overview of a Shipboard Weapons Systems

SN-1801A	The Stable Element, Mark 6—The Purpose of the Stable Element. (11 min.—1944.)
MN-7317A	The Computer Mark 1A—The Mark 37 System and Tracking the Target. (22 min.—1952.)
MN-7317D	The Computer 1A—Stabilization. (12 min.—1952.)
MN-8342A	Target Designation System, Mark VI—Scan Conversion. (12 min.—1958.)

CHAPTER 6

Basic Mechanical and Electrical Components

MN-6783A	Basic Mechanisms in Fire Control Computers—Part 1—Shafts, Gears, Cams, and Differentials. (20 min.—1953.)
SN-1726D	Introduction to Basic Mechanisms—Numerical Quantities. (20 min.—1943.)

CHAPTER 7

Synchros and Data Transmission Circuits

SN-1351L	Fire Control Mechanisms—Single Cam Follow-Up. (115 min.—1943.)
SN-1351M	Fire Control Mechanisms—Intermittent Oscillating Drive Follow-Up. (34 min.—1943.)
SN-1351N	Fire Control Mechanisms-Compensated Follow-Up. (42 min.—1943.)
SN-13510	Fire Control Mechanisms—Synchro Motor and Heart-Shaped Cam Follow-Up—Single Motor. (27 min.—1943.)
SN-1351P	Fire Control Mechanisms—Synchro Motor and Heart-Shaped Cam Follow-Up—Double Motor. (31 min.—1943.)

CHAPTER 8

Servomechanisms

MA-8581A	Servo Systems and Data Transmission—Part 1—Fundamentals of Servo. (17 min.—1956.)
MA-8581B	Servo Systems and Data Transmission—Part 2—Basic Principles of Positioning Servos. (33 min.—1956.)
MA-8581C	Servo Systems and Data Transmission—Part 3—Automatic Tracking and Data Transmission. (33 min.—1958.)
SN-1351J	Fire Control Mechanisms—Servo Motors and Dampers Control. (25 min.—1943.)

CHAPTER 9

Fundamentals of Gyroscopes

MN-1792A	The Gyro Compass—Principles of the Gyroscope. (10 min.—1944.)

SN-1801B	The Stable Element, Mark 6—General Functional Description. (25 min.—1943.)
SN-1801C	The Stable Element, Mark 6—Why the Gyro Axis Stays Vertical. (22 min.—1943.)

CHAPTER 10

Lead-Computing Sights and GFCS Mk 63

MN-6768	Gun Fire Control System Mark 63. (18 min.—1951.)

CHAPTER 11

Analog Computers

SN-1351A	Fire Control Mechanisms—Differential Gear. (14 min.—1943.)
SN-1351B	Fire Control Mechanisms—Disc Integrator and Telescopic Arm—Parts 1 and 2. (25 min.—1943.)
SN-1351C	Fire Control Mechanisms—Component Solver. (25 min.—1943.)
SN-1351D	Fire Control Mechanisms—Component Integrator. (24 min.—1943.)
SN-1351E	Fire Control Mechanisms—Screw Type Multiplier. (52 min.—1943.)
SN-1351F	Fire Control Mechanisms—Slide Type Multiplier. (35 min.—1943.)
SH-135G	Fire Control Mechanisms—Sector Type Multiplier. (28 min.—1943.)
SN-135H	Fire Control Mechanisms—Reciprocal Cam. (8 min.—1943.)
SN-135I	Fire Control Mechanisms—Three Dimensional Cam. (45 min.—1943.)
SN-135K	Fire Control Mechanisms—Limit Stop (Mechanical and Electrical). (8 min.—1943.)

CHAPTER 12

Introduction to Fire Control Radar

SN-1075	The Pulsing Transmitter—Radar No. 5. (40 frames—1942.)
SN-1079	The Indicator—Radar No. 9. (48 frames—1942.)
MN-5050A	Radar-Accuracy and Resolution-Range. (10 min.—1946.)
MN-5050B	Radar-Accuracy and Resolution—Bearing (16 min.—1946.)

CHAPTER 13

Fire Control Pulse Radar

MA-1704	Radio Antennas—Creation and Behavior of Radio Waves. (11 min.—1942.)

MN-9329A	Radio Antenna Fundamentals—Part 1. (27 min.—1952.)
MN-9329B	Radio Antenna Fundamentals—Part 2. (16 min.—1952.)

CHAPTER 15

Submarine Fire Control

MN-6743	Introduction to Torpedoes. (14 min.—1950.)
MN-2850	Gyroscopic Creep and Precession in Torpedoes. (15 min.—1943.)

CHAPTER 16

Administrative Duties

MN-10043A	Planned Maintenance System—Introduction. (20 min.—Color—Sound—Unclassified—1965.)
MN-10043B	Shipboard Maintenance Data Collection System—Standard Maintenance and Materiel Management. (20 min.—Color—Sound—Unclassified—1965.)
MN-6947	Security Control—You Never Can Tell. (36 min.—1962.)
FN-8801	Coordinated Shipboard Allowance List. (19 min.—1959.)

CHAPTER 17

Maintenance and Troubleshooting

MA-2594	Soldering Electrical Connections. (18 min.—1943.) USAF TF1-402.
MN-1540P	Radio Technician Training—Tube Tester Operation. (9 min.—1944.)
MN-1540S	Radio Technician Training—Volt Ohmmeter Operation. (15 min.—1944.)
MA-7812A	Circuit Testing with Meters and Multimeters—Theory. (35 min.—1951.) US Army TF 11-1666.
MA-7812B	Circuit Testing with Meters and Multimeters—Practical Application. (33 min.—1951.) US Army TF 11-1667.
MA-8687B	Reading Multimeter Scales. (6 min.—1956.) US Army TF 11-2392.
MN-8016E	Basic Electricity.—Basic D-C Meter Movement (3 min.—1954.)

APPENDIX II

EQUIPMENT NOMENCLATURE

Nomenclature designations are used primarily as the short title of equipments. These designations are unclassified, whereas the actual name of the equipment may sometimes be classified.

The nomenclature system used by the military services to identify electronic equipment and independent units that are not part of specific equipment is called the Joint Electronic Type Designation System (AN system) for communication and electronic equipments.

The AN nomenclature is assigned to:

1. Complete sets of equipment and major components of military design.
2. Groups of articles of either commercial or military design which are grouped for a military purpose.
3. Major articles of military design which are not a part of, or used with, a set.
4. Commercial articles when nomenclature will facilitate military identification or procedures.

AN nomenclature is not assigned to:

1. Articles cataloged commercially except when nomenclature will facilitate military identification or procedures.
2. Minor components of military design for which other adequate means of identification are available.
3. Small parts such as capacitors and resistors.
4. Articles having other adequate identification in American War Standards or Joint Army-Navy specifications.

EQUIPMENT INDICATOR LETTERS

Complete systems of equipments are designated by three indicator letters that follow AN/ and signify (1) Kind of installation, (2) Type of equipment, and (3) Purpose. Using AN/SPG-49 as an example, check the equipment indicator letters in the following table:

EQUIPMENT INDICATOR LETTERS

Installation	Type of Equipment	Purpose
A–Airborne (installed and operated in aircraft)	A–Invisible light, heat radiation	A–Auxiliary assemblies (not complete operating sets)
B–Underwater mobile, submarine	B–Pigeon	B–Bombing
C–Air transportable	C–Carrier	C–Communications (receiving and/or
	D–Radiac	
	E–Nupac	

Installation	Type of equipment	Purpose
(inactivated; do not use) D–Pilotless carrier F–Fixed G–Ground, general ground use (includes two or more ground installations) K–Amphibious M–Ground, mobile (installed as operating unit in a vehicle which has no function other than transporting the equipment) P–Pack or portable (animal or man) S–Water surface craft T–Ground, transportable U–General utility (includes two or more general installation classes, airborne, shipboard, and ground) V–Ground, vehicular (installed in vehicle designed for functions other than carrying electronic equipment, etc., such as tank) W–Water surface and underwater	F–Photographic G–Telegraph or teletype I–Interphone or public address J–Electromechanical (not otherwise covered) K–Telemetering L–Countermeasures M–Meteorological N–Sound in air P–Radar Q–Sonar or underwater sound R–Radio S–Special types, magnetic, etc., or combinations of types. T–Telephone (wire) V–Visual or visible light W–Armament (peculiar to armament, not otherwise covered) X–Facsimile or television Y–Data processing	transmitting) D–Direction finder G–Fire control or searchlight directing H–Recording (photographic, meteorological, or sound) L–Searchlight control (inactivated; use "G") M–Maintenance and test assemblies (including tools) N–Navigational aids (including altimeters, beacons, compasses, racons, depth sounding, approach, and landing_ P–Reproducing (photographic and/or sound) Q–Special, or combination or purposes R–Receiving, passive detecting S–Detecting and/or range and bearing T–Transmitting W–Control X–Identification and recognition

AN indicates the equipment was assigned the type number in the AN system. "S" of the indicator letters, as shown in the installation column, means that the equipment is installed on a water surface craft. "P" in the type of equipment column signifies that the equipment is radar; and "G" in the purpose column indicates that the equipment is used for fire control or searchlight directing. The number 49 following the letters shows that it is the forty-ninth model designed for surface radar equipment. Any modification to the equipment will be indicated by adding A, B, etc., after the model number.

Component Indicators

Ind. ltr.	Family name	Examples of use
AB	Supports, antenna	Antenna mounts, mast bases, mast sections, towers, etc.
AM	Amplifiers	Power, audio, interphone, radiofrequency, video, electronic control, etc.
AS	Antennae, complex	Arrays, parabolic type, masthead, etc.
AT	Antennae, simple	Whip or telescopic, loop dipole, reflector, etc.
BA	Battery, primary type	B batteries, battery pack, etc.
BB	Battery, secondary type	Storage batteries, battery packs, etc.
BZ	Signal devices, audible	Buzzers, gongs, horns, etc.
C	Controls	Control box, remote tuning controls, etc.
CA	Commutator assemblies, sonar.	Peculiar to sonar equipment.
CB	Capacitor bank	Used as a power supply.
CG	Cable assemblies, r-f	R-f cables, waveguides, transmission lines, etc., with terminals.
CK	Crystal kits	A kit of crystals with holders.
CM	Comparators	Compares two or more input signals.
CN	Compensators	Electrical and/or mechanical compensating, regulating, or attenuating apparatus.
CP	Computers	A mechanical and/or electronic mathematic calculating device.
CR	Crystals	Crystal in crystal holder.
CU	Couplers	Impedance coupling devices, directional couplers, etc.
CV	Converters (electronic)	Electronic apparatus for changing the phase, frequency, or from one medium to another.
CW	Covers	Cover, bag, roll, cap, radome, nacelle, etc.
CX	Cable assemnlies, Non-r-f	Non-r-f cables with terminals, test leads, also composite cables of r-f and non-r-f conductors.
CY	Cases and cabinets	Rigid and semirigid structure for enclosing or carrying equipment.
D	Dispensers	Chaff dispensers.
DA	Load, dummy	R-f and non-r-f test loads.
DT	Detecting heads	Magnetic pickup device, search coil, hydrophone, etc.
DY	Dynamotors	Dynamotor power supply.
E	Hoists	Sonar hoist assembly.
F	Filters	Bandpass, noise, telephone, wave traps, etc.
FN	Furniture	Chairs, desks, tables, etc.
FR	Frequency measuring devices.	Frequency meters, tuned cavity, etc.
G	Generators, power	Electrical power generators without prime movers. (see PU and PD.)
GO	Goniometers	Goniometers of all types.
GP	Ground rods	Ground rods, stakes, etc.
H	Head, hand, and chest sets	Includes earphone.
HC	Crystal holder	Crystal holder, less crystal.
HD	Air conditioning apparatus	Heating, cooling, dehumidifying, pressure, vacuum devices, etc.
ID	Indicators, non-cathode ray tube.	Calibrated dials and meters, indicating lights, etc. (See IP.)
IL	Insulators	Strain, standoff, feed-through, etc.
IM	Intensity measuring devices.	Includes SWR gear, field intensity and noise meters, slotted lines, etc.

Component Indicators—Continued.

Ind. ltr.	Family name	Examples of use
IP	Indicators, cathode ray tube	Azimuth, elevation, panoramic, etc.
J	Junction devices.	Junction, jack, and terminal boxes, etc.
KY	Keying devices.	Mechanical, electrical, and electronic keyers, coders, interrupters, etc.
LC	Tools, line construction . . .	Includes special apparatus such as cable plows.
LS	Loudspeakers	Separately housed loudspeakers, intercommunication station.
M	Microphones	Radio, telephone, throat, hand, etc.
MA	Magazines.	Magnetic tape or wire.
MD	Modulators	Device for varying amplitude, frequency, or phase.
ME	Meters, portable	Multimeters, volt-ohm-milliammeters, vacuum tube voltmeters, power meters, etc.
MF	Magnets or magnetic field generators	Magnetic tape or wire eraser, electromagnet, permanent magnet, etc.
MK	Miscellaneous kits	Maintenance, modification, etc., except tool and crystal. (See CK, TK.)
ML	Meteorological devices	Barometer, hygrometer, thermometer, scales, etc.
MT	Mountings	Mountings, racks, frames, stands, etc.
MX	Miscellaneous	Equipment not otherwise classified. Do not use if better indicator is available.
O	Oscillators	Master frequency, blocking, multivibrators, etc. (For test oscillators, see SG).
OA	Operating assemblies	Assembly of operating units not otherwise covered.
OC	Oceanographic devices	Bathythermographs.
OS	Oscilloscope, test	Test oscilloscopes for general test purposes.
PD	Prime drivers	Gasoline engines, electric motors, diesel motors, etc.
PF	Fittings, pole	Cable hangar, clamp, protectors, etc.
PG	Pigeon articles	Container, loft, vest, etc.
PH	Photographic articles	Camera, projector, sensitometer, etc.
PP	Power supplies	Nonrotating machine type such as vibrator pack, rectifier, thermoelectric, etc.
PT	Plotting equipment except meteorological, maps etc	Boards, maps, plotting table, etc.
PU	Power equipment except dynamotors, motor generator etc.	Rotating power equipment; motor generator.
R	Receivers	Receivers, all types except telephone.
RC	Reels	Reel, cable. (See RL.)
RD	Recorder-reproducers	Sound, graphic, tape, wire, film, disk facsimile, magnetic, mechanical, etc.
RE	Relay assemblies	Electrical, electronic, etc.
RF	Radiofrequency component	Composite component of r-f circuits. Do not use if better indicator is available.
RG	Cables, r-f, bulk	R-f cable, waveguides, transmission lines, etc., without terminals.
RL	Reeling machines	Mechanisms for dispensing and rewinding antenna or field wire, recording wire or tape, etc.
RO	Recorders.	Sound, graphic, tape, wire, film, disk, facsimile, magnetic, mechanical, etc.

Component Indicators–Continued

Ind. ltr.	Family name	Examples of use
RR	Reproducers.	Sound, graphic, tape, wire, film, disk, facsimile, magnetic, mechanical, etc.
RR	Reflectors	Target, confusion, etc., except antenna reflectors, (See AT.)
RT	Receiver and transmitter . .	Radio and radar transceivers, composite transmitter and receiver, etc.
S	Shelters.	House, tent, protective shelter, etc.
SA	Switching devices	Manual, impact, motor-driven, pressure-operated, etc.
SB	Switchboards	Telephone, fire control, power, panel, etc.
SG	Generators, signal	Test oscillators, noise generators, etc. (See O)
SM	Simulators.	Flight, aircraft, target, signal, etc.
SN	Synchronizers	Equipment to coordinate two or more functions.
ST	Straps.	Harness, straps, etc.
SU	Optical Devics	Telescope, periscope, projectors, and boresighting scope.
T	Transmitters	Transmitters, all types except telephone.
TA	Telephone apparatus	Miscellaneous telephone equipment.
TD	Timing devices.	Mechanical and electronic timing devices, range device, multiplexes, electronic gates, etc.
TB	Towed Body	Towed underwater body, paravanes, etc.
TC	Towed Cable	Faired cable, etc.
TF	Transformers.	Transformers when used as separate items.
TG	Positioning devices	Tilt and/or train assemblies.
TH	Telegraph apparatus	Miscellaneous telegraph apparatus.
TK	Tool kits	Miscellaneous tool assemblies.
TL	Tools	All types except line construction. (See LC.)
TN	Tuning units.	Receiver, transmitter, antenna, tuning units, etc.
TR	Transducers.	Magnetic heads, phono pickups, sonar transducers, vibration pickups, etc. (See H, LS, and M).
TS	Test Items	Test and measuring equipment not otherwise included; boresighting and alignment equipment.
TT	Teletypewriter and facsimile apparatus	Miscellaneous tape, teletype, facsimile equipment, etc.
TV	Tester, tube.	Electronic tube tester.
TW	Tapes and recording wires .	Recording tape and wire, splicing, electrical insulating tape, etc.
U	Connectors, audio and power	Unions, plugs, sockets, adapters, etc.
UG	Connectors, r-f	Unions, plugs, sockets, choke couplings, adapters, elbows, flanges, etc.
V	Vehicles	Carts, dollies, trucks, trailers, etc.
VS	Signaling equipment, visual	Flag sets, aerial panels, signal lamp equipment, etc.
WD	Cables, two-conductor	Non-r-f wire, cable and cordage in bulk. (See RG.)
WF	Cables, four-conductor . . .	Non-r-f wire, cable and cordage in bulk. (See RG.)
WM	Cables, multiple-conductor.	Non-r-f wire, cable and cordage in bulk. (See RG.)
WS	Cables, single-conductor . .	Non-r-f wire, cable and cordage in bulk. (See RG.)
WT	Cables, three-conductor. . .	Non-r-f wire, cable and cordage in bulk. (See RG.)
ZM	Impedance measuring devices	Used for measuring Q, C, L, R, or PF, etc.

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